

Article

Microclimatic Effects on the Preservation of Finds in the Visitor Centre of the Archaeological Site 1a Imperial Palace Sirmium

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Abstract: When an archaeological site is roofed over for the better display of the finds and more comfortable experience of the audience, the intervention undoubtedly changes the microclimatic conditions in the site. Although sudden changes in microclimatic factors are known to damage and/or destroy archaeological finds, their impact and its analysis are neglected in Serbia. There is no continuous monitoring and control of microclimatic conditions or their impact on architectural remains in archaeological sites. Accordingly, the values of microclimatic parameters of temperature and relative humidity and their daily oscillations are examined in this paper through microclimatic monitoring in the Visitor Center of the Archaeological Site 1a Imperial Palace Sirmium, which is a cultural asset of exceptional importance. Moreover, microbiological analyses determine the degree of contamination of architectural findings. The aim of this paper is to determine whether the microclimatic regime in the Visitor Center of the Archaeological Site 1a Imperial Palace Sirmium is in accordance with European standards and recommendations on optimal microclimatic conditions for the presentation and preservation of cultural heritage collections. The findings showed that during the phase of microclimatic monitoring (February–April 2021), air humidity was almost constantly above the levels set by standards and recommendations for museum collections (>60%). The highest levels of air humidity, amounting to 93%, were recorded in February, with daily oscillations of up to 30%; the lowest recorded temperature was 0.3 °C, with the maximum daily oscillations of 6 °C. Microbiological analysis revealed great diversity in the deterioration level of the finds, which can be attributed to the time lapse between the last conservation and the present. The comparative analysis of the results of microclimatic monitoring and microbiological analysis identified high levels of relative air humidity as the dominant factor in the increased microbiological contamination of the finds. It is also concluded that the continuous monitoring of the microclimatic parameters of temperature and relative humidity during the usage of the facility is necessary so as to enable sustainable presentation and preservation of findings.

Keywords: protective structures; microclimatic monitoring; microbiological deterioration of architectural finds; Archaeological Site 1a Imperial Palace Sirmium



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1. Introduction

Modern solutions for protecting, preserving and displaying archaeological finds belonging to architectural heritage in situ are not uncommon in global practice. Since 2000 and the European Landscape Convention, ratified by Serbia in 2011, the display of the finds in situ is recognised as a potential for promoting creative industries and cultural tourism. Along the same line, cultural heritage is recognised as an important factor in city branding and the strategies of cities for economic growth and development. The in situ presentation of the finds poses a challenge before numerous professionals involved in the interdisciplinary and comprehensive process, from those involved in archaeological research to those specialised in displaying the finds and opening sites for the public.

Putting the first instances of sheltering archaeological sites in the early 19th century aside, most protective structures that served both the purpose of preserving the finds and their display to the public in situ were erected in the 1960s. However, the development of protective structures and visitor centres in archaeological sites has been particularly intensified in the last decade of the 20th century and in the early 21st century, with the new concept of musealisation, based on the tendency to display the finds to the visitors in situ. Depending on the characteristics of the local climate and the types of finds to be displayed, one can opt for open protective structures (canopies and overhangs), semi-open ones (shelters) or those fully closed and with a controlled access, in the shape of a building with a permanent museological display of the finds throughout the year. Experience in European and domestic protective practices differ as regards the application of protective structures in archaeological sites [1]. In some sites, the erection of these structures has raised new issues, directly or indirectly affecting the preservation of the finds [2–6]. One of the issues has most certainly been a sharp change in microclimatic conditions and the establishment of new microclimatic regime. Such climatic shock can cause the materials of the finds to deform, thus damaging the finds [7]. In addition, frequent oscillations in temperature and relative air humidity result in the chemical, mechanical and biological deterioration of the finds. Having all that in mind, inside protective structures and permanent facilities built in archaeological sites functioning as museums in situ, securing proper microclimatic conditions for both preserving and displaying artifacts and providing comfort for the visitors is of the utmost importance. Microclimatic conditions can only be controlled indoors, i.e., in closed protective structures. As opposed to the extensive number of papers discussing the optimum microclimatic conditions for museum collections on display [8–12] or those in historic buildings repurposed as museums [13–17], depots [18] and archives and libraries [19], scientific research on monitoring microclimatic regimes inside protective structures and visitor centres on archaeological sites that has been presented and published in a paper is less present, although the problems of unbalanced microclimatic conditions for the preservation and presentation of findings are evident [20–22]. What makes archaeological sites specific is primarily the impact of the environmental conditions (ground waters, for example). In addition to microclimatic conditions in the site, the preservation of architectural remains is also determined by the characteristics of the building materials, which are usually porous, hygroscopic, inorganic and especially sensitive to the oscillations in the relative air humidity, since it disturbs the fine balance of humidity in them [7]. To adapt to the constant change of the surrounding conditions, these materials need to absorb and lose moisture. The change in the usual content of moisture results in dimensional change that causes physical damage, breakage and deformation. Large temperature oscillations are the cause of chemical deterioration, while high levels of relative air humidity bring about the biological deterioration of the finds [11].

Since the environmental conditions are singular, i.e., differ from site to site, the values of microclimatic parameters of air temperature and relative air humidity are specifically monitored in the Visitor Centre of the Archaeological Site 1a Imperial Palace Sirmium. Microclimatic monitoring and microbiological research there were triggered by the discovery of microorganisms and biological agents on the finds. Due to the large scope of finds in the site, this paper focuses solely on the research of the microclimatic parameters, air temperature and relative air humidity and their impact on the preservation of the biologically contaminated ancient mosaics.

The aim of this paper is to establish by microclimatic monitoring whether the values of temperature and relative humidity parameters and their oscillations on a daily basis in the Visitor Center of the Archaeological Site 1a Imperial Palace Sirmium are in accordance with recommended values in European regulations, recommendations and guidelines for the preservation of cultural heritage collections, as well as to examine the degree of biological contamination of the ancient mosaics. By means of a comparative analysis of microclimatic monitoring and microbiological study results, this research is to determine whether the conditions in situ pose a hazard to the preservation of the displayed finds. Accordingly, the

test results are the starting point for the establishment of guidelines for the improvement of the microclimatic regime in the Visitor Center of the Archaeological Site 1a Imperial Palace Sirmium.

2. Recommended and Standard Microclimatic Conditions in Museums

The recommendations and standards of optimum microclimatic conditions have changed from the approach founded on ideal, constant microclimatic environmental conditions that guarantee the preservation of the artifacts/finds to that favouring conditions acceptable both from the perspective of preservation of the finds and from the point of view of visitors and their comfort during the visit.

With the development of heating, ventilation and conditioning systems, the last century saw the growing number of studies on the impact of the microclimatic conditions of the environment on the preservation of museum artifacts, serving as a basis for developing conditions optimisation models. The first approach—the statistical model of optimising the artifacts preservation and display conditions in the museum—promotes the establishment of a constant, permanent microclimate throughout the year with the view to reduce the risk of their deterioration [23]. Therefore, the optimum microclimatic parameters should be determined for each artifact and its building material to preserve it. Consequently, museum collections are sorted by the type of material the artifacts are made of. For heterogenous, composite materials, the mean value of the microclimatic parameters was used. Based on the research carried out by Garry Thompson, an authority on the subject, the optimum temperatures for displaying most artifacts are 19 °C in winter and 24 °C in summer, coupled with the recommended year-round relative air humidity ranging between 50% and 55%, with a maximum allowed oscillation of 5% [23]. Although the constant microclimate proposed by this model secures the preservation of the finds, such a model is uneconomical as regards the energy consumption for heating, air-conditioning and dehumidification, coupled with the high maintenance costs. To reach the sustainable solution, it is necessary to make compromises between the optimum values that secure the preservation of artifacts (based on the characteristics of their building materials) and the energy consumption for heating, air-conditioning and providing comfort for visitors. The question is how to provide the optimum conditions for the display of finds without large investment in thermal and technical systems, so that the solution can be financially acceptable, energy-efficient and environmentally friendly. This question is still pending for an answer, lying at the core of the dynamic model of microclimate optimisation.

The statistical model is nowadays abandoned, although some museums still keep their collections in a constant, stable microclimate [19]. Large energy consumption and CO₂ emissions were the reason for the adoption of the dynamic model, where variations in climatic parameters are allowed. However, the variation curve must not be extreme but should be kept within the recommended ranges of the allowed daily oscillations in microclimatic parameters. The dynamic model is based on the concept of energy sustainability and environment protection and promotes the reduction of CO₂ emission and the use of renewable energy sources. The optimization of the indoor microclimate in this model is achieved passively by applying the concept of “passive conditioning” [11]. The concept involves good thermal insulation, a hermetic cover and a high thermal and hygric inertia of the entire structure.

The dynamic model has yielded several standards and recommendations for modelling microclimatic conditions. All of them are characterised by a small difference in the recommended ranges of parameters and the allowed oscillation in the temperature and relative humidity values on a daily and seasonal basis, but substantially, they are all based on the same principle—the dynamic model. Among them are the British and Italian standards, standards of the European Committee for Standardization (CEN), recommendations from organisations dealing with the preservation and conservation of artifacts and finds and those suggested by different associations and organisations. Since this is a multidisciplinary area and calls for the cooperation of experts from different fields of

expertise, each organisation puts into focus its own area of expertise when prescribing standards, guidelines and recommendations.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has issued a set of regulations for museums, archives and libraries, depending on the type of collection and the category of a facility [24]. The document defines five classes of microclimatic modes based on the acceptable ranges of temperature and relative air humidity during short-term oscillations and seasonal adjustments, taking into account the risks for the finds. The most controlled conditions are in Class AA, while Class D has the most relaxed conditions, where only the air humidity is controlled (see Table 1).

Table 1. Proposed air temperature and relative air humidity values in museums according to the ASHRAE. Source: [24].

Set Point or Annual Average	Maximum Fluctuations and Gradients in Controlled Spaces			Collection Risks and Benefits
	Class of Control	Short Fluctuations Plus Space Gradients	Seasonal Adjustments in System Set Point	
50% rh (or historic annual average for permanent collections)	AA Precision control, no seasonal changes, with system failure fallback	+/-5% rh, +/-2 °C	Relative humidity no change Up 5 °C; Down 5 °C	No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50% rh exceeds a critical relative humidity. Chemically unstable objects unusable within decades.
Temperature set between 15 and 25 °C	A Precision control, some gradients or seasonal changes, not both, with system failure fallback	+/-5% rh, +/-2 °C	Up 10% rh, down 10% rh Up 5 °C; Down 10 °C	Small risk of mechanical damage to high vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs and books. Chemically unstable objects unusable within decades.
		+/-10% rh, +/-2 °C	Rh no change Up 5 °C; down 10 °C	
<i>Note:</i> Rooms intended for loan exhibitions must handle set point specified in loan agreement, typically 50% rh, 21 °C, but sometimes 55% or 60% rh	B Precision control, some gradients plus winter temperature setback	+/-10% rh, +/-5 °C	Up 10% rh, down 10% rh Up 10 °C; but not above 30 °C	Moderate risk of mechanical damage to high vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 30 °C, but cold winter periods double life.
	C Prevent all high-risk extremes	Within 25 to 75% rh year-round; temperature rarely over 30 °C, usually below 25 °C		High risk of mechanical damage to high vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts, some books; tiny risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 30 °C, but cold winter periods double life.
	D Prevent dampness	Reliably below 75% rh		High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; avoids high-humidity delamination and deformations, especially in veneers, paintings, paper and photographs. Mould growth and rapid corrosion avoided. Chemically unstable objects unusable within decades, less if routinely at 30 °C, but cold winter periods double life.

For the purpose of this paper, air temperature and relative air humidity values taken in the Visitor Centre of Archaeological Site 1a Imperial Palace Sirmium are analysed against the recommendations and guidelines of the International Council of Museums—Committee for Conservation (ICOM-CC) and the International Institute for Conservation of historic and artistic works (ICC) declaration on the proposed values of microclimatic conditions securing the preservation of artefacts issued by the Australian Institute for the Conservation of Cultural Material (AICCM) and the document on the preservation of hygroscopic material issued by the European Biyot Group in 2014 [25]. According to AICCM, the recommended temperature range for most collections is 15–25 °C with acceptable daily fluctuations +/-4 °C, while the relative humidity is in the range of 45–55% (40–60%) with allowed daily variations +/-5 %. For the stability of objects containing hygroscopic materials, a temperature of 16–25 °C and a stable relative air humidity in the range of 40–60% with fluctuations not exceeding ±10% for 24 h in this range are

recommended. The declaration notes that guidelines for the long-term display and storage of artifacts/finds should be established in line with local climate.

3. Characteristics of Serbian Climate

The climate in Serbia is continental, conditioned by its geographical position, the terrain and other local characteristics of the region. All four seasons are present. Autumn is warmer than spring and boasts longer sunny periods. Winter is not so sharp. Spring is rainy and it abruptly turns into summer. Data on the Serbian climate are taken from the report of the Republic Hydrometeorological Service of Serbia [26].

Between 1961 and 1990, the average air temperature in Serbia in the areas lower than 300 m of altitude was 10.9 °C. The highest temperatures in these decades were measured in July, ranging between 37 °C and 42.3 °C in lower altitudes, while the lowest ranged between −30.7 °C and −21.0 °C [27]. The warmest month was July with the average temperature of 22 °C, and the coldest was January with the average temperature of 0 °C.

The annual solar insolation in Serbia is between 1500 and 2200 insolation hours. It is longest in July and August (with the largest number of insolation hours), and shortest in December and January, when the cloudiness is high.

Precipitation is inconsistent and ranges from 540 mm to 820 mm a year in lower altitudes, with more than 1000 mm in upper regions, which leads to the conclusion that the precipitation grows with altitude [28]. June is the rainiest month, and February or October are the driest. The snow cover tends to form from November to March, most likely in January.

Typical winds in Serbia are northwest, west and southeast winds. The latter is locally called *Košava*, and it is a strong autumn and winter wind that brings dry and cold weather.

4. The Display of Finds in the Visitor Centre of the Archaeological Site 1a Imperial Palace Sirmium

On the site of the ancient city of Sirmium, the present-day Sremska Mitrovica, the remains of a royal palace were uncovered in 1957 during protective excavations and mobilisation before laying foundations for a residential block-of-flats, after which the works were cancelled [29]. The research was continued in 1974 and 1976, when it was concluded that the remains belonged to a palace complex. The dating was then conducted, and the timeline of its construction was determined [30]. The royal complex, comprising the site marked as 1a Imperial Palace, was built in the late 3rd century and during most of the 4th century, when the city reached its heyday. Ancient Sirmium, at the time, was an important strategic point on the road connecting the eastern and the western parts of the empire. The actual position of the royal palace, close to the circus, and the similarity in architectural forms and functions with other palace complexes of the time point to the royal residence. The existence of central heating, sewage and water-supply systems, rich architectural decoration based on 350 m²-large floor mosaics with geometric ornaments [31], fragments of frescoes with floral motives, multi-coloured marble and imported porphyry, as well as other remains of material culture in the royal palace in Sirmium, are all of exceptional importance for understanding the building technique of the time, as well as the technological scope and the way of life in the ancient period on the territory of the present-day Serbia.

Architectural remains of the royal complex in Sirmium were displayed to the public in the open for 52 years, when it was decided that a structure serving the purpose of a visitor centre should be raised above the site of the royal palace. The Visitor Centre was meant to display antique remnants and mosaics and protect the site from weathering (rain, snow, the sun, wind) that causes the devastation of the finds. The project was financially supported by the Serbian ministries of culture and economy and regional development. The Visitor Centre was built and opened to the public on 14 December 2009, while the conservation works on mosaics have been carried out in phases and are still ongoing. The Visitor Centre building erected above the architectural remains of the royal palace was designed by architects and conservators Adrijana Škorić and Ivan Filipović (Figure 1).

It is constructed in three levels, with a total area of 2680 m². On the ground floor, the entrance area comprising a souvenir shop and a coffee shop opens to a gallery from which the whole site can be seen. The ramp from the gallery leads to the lowest level with the architectural remains of the palace. However, the access is currently restricted due to the ongoing conservation works on the mosaics. The gallery on the highest level offers a new point of view to the site. The structure above the architectural remains of the royal palace is not thermally insulated. It is supported on RC walls, topped with brick walls supporting the roof made of braced glued laminated lumber covered with sheet metal and polycarbonate slabs by segments. Being transparent, polycarbonate slabs allow the high insolation of the interior, causing the greenhouse effect, so the interior became prone to the expansion of microorganisms (lichens) and low vegetation [32]. The situation called for additional investment in replacing the roof cover material of choice. The intervention, however, did not resolve the existing issues since the existing polycarbonate slabs were simply covered with sheet metal. Covering the site and forming the closed space above it caused the change in microclimatic conditions. That caused the architectural remains to suddenly dry off, at the same time increasing the humidity in the closed part of the site and in certain zones on display. The remains of the royal palace have been permanently compromised. Unbalanced microclimate, temperature and humidity fluctuations and the side effects in the form of microorganisms and low vegetation growing on the finds pose the main hazard for the preservation as indicators of compromised cultural heritage. Monitoring microclimatic conditions in the Visitor Centre would determine the values of the microclimatic parameters, which would then serve as the basis for assessing the risks for the further display of the finds in such conditions. Mosaics M2, M23 and M34 will also be subjected to monitoring to determine the level of their contamination.



(a)



(b)

Figure 1. Visitor Centre of the Archaeological Site 1a Imperial Palace Sirmium: (a) viewed from the outside; (b) the interior.
Source: A. Ugrinović.

5. Materials and Methods

5.1. Microclimate Monitoring

In the Visitor Centre of the Archaeological Site 1a Imperial Palace Sirmium, continuous measurements of indoor and outdoor values of microclimatic parameters of temperature and relative air humidity were performed from February to April. The reading interval was 30 min. The data were collected by the Testo 174h device (Figure 2a) and the PCE-FWS-20 meteorological station (Figure 2b).

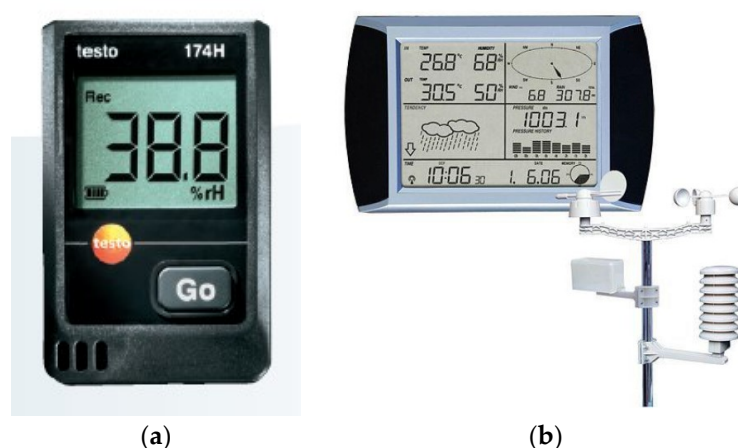


Figure 2. The devices used for monitoring microclimate: (a) Data logger Testo 174h, Source: [33]; (b) Meteorological station PCE-FWS-20. Source: [34].

The indoor values of microclimate parameters were read by the Testo 174h device. This device has a measuring range for temperature from -20 to $+70$ °C (with 0.5 °C accuracy) and for relative air humidity, from 0 to 100% (accuracy of 3%). The memory capacity of the data logger TESTO 174h is $16,000$ readings. Testo data loggers are placed at 30 cm (DL1) and at 350 cm from the ancient mosaic floor (DL2) in order to determine the vertical distribution of temperature and relative air humidity.

The meteorological station PCE-FWS-20 is placed on the southeastern gable wall of the Visitor Centre for the purpose of measuring outdoor microclimate. The memory display that stores the measured data and is connected via radio waves with the meteorological station is on the interior side of the property, on the southeastern wall, at the upper-level gallery. The vertical distance of the meteorological station display from the level with the Imperial Palace architectural remains is about 9 m. The PCE-FWS-20 instrument for reading outdoor values of temperature and relative air humidity measures the range from -40 °C to 65 °C and from 10 to 90% , while the traceable indoor microclimate values range from 0 to $+50$ °C and from 10 to 90% .

5.2. Mycological Analyses

5.2.1. In Situ Optical Microscopy

The studied mosaics were investigated at the site, using Delta Optical Smart 5MP PRO digital USB microscope (Delta optical). In situ microscopy was applied directly on areas with visible biodeterioration symptoms. Image processing was carried out via Delta Optical SmartAnalysis Pro software.

5.2.2. Sampling Methods

Non-invasive adhesive tape was applied to the mosaics' surface and, in order not to damage the investigated object, removed with a steady force [35]. Samples were then attached to microscopic slides and preserved in sterile containers for further microscopic analyses.

In order to sample viable fungal propagules, selected areas (approximately 10 cm² surface) with biodeterioration symptoms were wiped with sterile cotton swabs and inoculated and transferred in sterile bags to laboratory. Samples were inoculated on Malt extract agar (MEA) and incubated in thermostat (UE 500, Memmert) at 25 °C for 7 days. After incubation period, colonies were enumerated to establish the number of colony-forming units per units of surface (CFU cm⁻²), and pure fungal cultures were obtained from primary isolates.

Aeromycological sampling was carried out by Koch's sedimentation method [36]. Petri plates (9 cm Ø) with MEA medium were opened and exposed for 15 min in the proximity of the studied mosaics. Afterwards, petri plates were closed, sealed with parafilm and transferred in sterile bags to laboratory. After incubation period (25 °C, 7 days), viable

colonies were enumerated, and total fungal load (CFU m⁻³ of air) was evaluated according to the following formula [37,38]:

$$N = 5 \times a \text{ (bt)}^{-1} \times 10^4$$

where N = total number of CFU m⁻³, a = number of colonies per Petri dish, b = dish square centimetre, t = exposure time (min.)

5.2.3. Fungal Identification

Adhesive tape samples were mounted in Lactophenol Cotton Blue–glycerol mixture and observed under a light microscope. Isolates obtained via both cotton swabs and aeromycological sampling were identified based on macromorphology of 7-day-old colonies and the micromorphology of reproductive structures were observed by optical microscope Zeiss Axio Imager M.1 with AxioVision Release 4.8.1 software. Identification was performed using identification keys [39–41].

6. The Results of Microclimate Monitoring and Microbiological Research

6.1. Microclimate in the Visitor Centre of Archaeological Site 1a Imperial Palace Sirmium

The microclimate monitoring results for the period between 8 February and 5 April 2021 are shown for each measurement device, respectively. The values read from the Testo data logger DL1 (placed at 30 cm from the floor mosaic elevation) and from the DL2 (placed at 350 cm from the floor mosaic elevation) are shown in Figure 3. The data were processed by Testo Comfort Software Basic 5.0. The mean temperature values during the monitoring period were 8 °C (DL1) and 8.21 °C (DL2), while the average relative air humidity values were about 75% (DL1) and 73.55% (DL2). The maximum temperature values were recorded on 1 April, and they amounted to 16 °C (DL1) and 16.90 °C (DL2), while the lowest temperatures were read on 14 February and were 0.40 °C (DL1) and 0.30 °C (DL2). The highest relative humidity values were recorded on 11 February and were 93.40% (DL1) and 93.50% (DL2), while the lowest relative humidity values were 51.70% (DL1) and 48.70 (DL2). Based on the microclimate monitoring results indoors, it may be stated that the values read from devices DL1 and DL2 are approximately the same. However, it is evident that the temperature is increasing and the relative humidity decreasing with height. The greatest daily temperature oscillation was 6 °C, while the oscillations in the relative air humidity were as high as 30% daily. According to the daily oscillations in the microclimatic parameters envisaged in the recommendations and guidelines for the conservation of museum collections, relative air humidity oscillations are much higher than the recommended range (optimal +/−5%, for hygroscopic materials max. +/−10%). During the longer period of temperature measurement, daily variations were acceptable and within the permitted range. The relative air humidity was above the recommended limit value of 60%. No temperature values below 0 were recorded at measurement positions and therefore the materials of which the mosaic structure is made were not exposed to stress due to the freeze–thaw cycle.

From the meteorological station PCE-FWS-20, the outdoor values of temperature and relative air humidity were read, and the indoor parameter values were measured at 8 m elevation from the ancient mosaic floor. The charts show the comparative outdoor and indoor values of microclimatic parameters of temperature (Figure 4) and relative air humidity (Figure 5). The data were processed by EasyWeather. The outdoor temperature in the measurement period ranged from −7.6 °C to 26.2 °C, while inside the Imperial Palace, it was from 4.2 °C to 18.2 °C. The relative air humidity varied from 15% to 99% indoors and from 38% to 79% outdoors. Based on the monitoring and comparative analysis of indoor and outdoor climate conditions, it was established that indoor variations of relative air humidity and temperature were substantially smaller, but the changes outdoors affected the indoor microclimate.

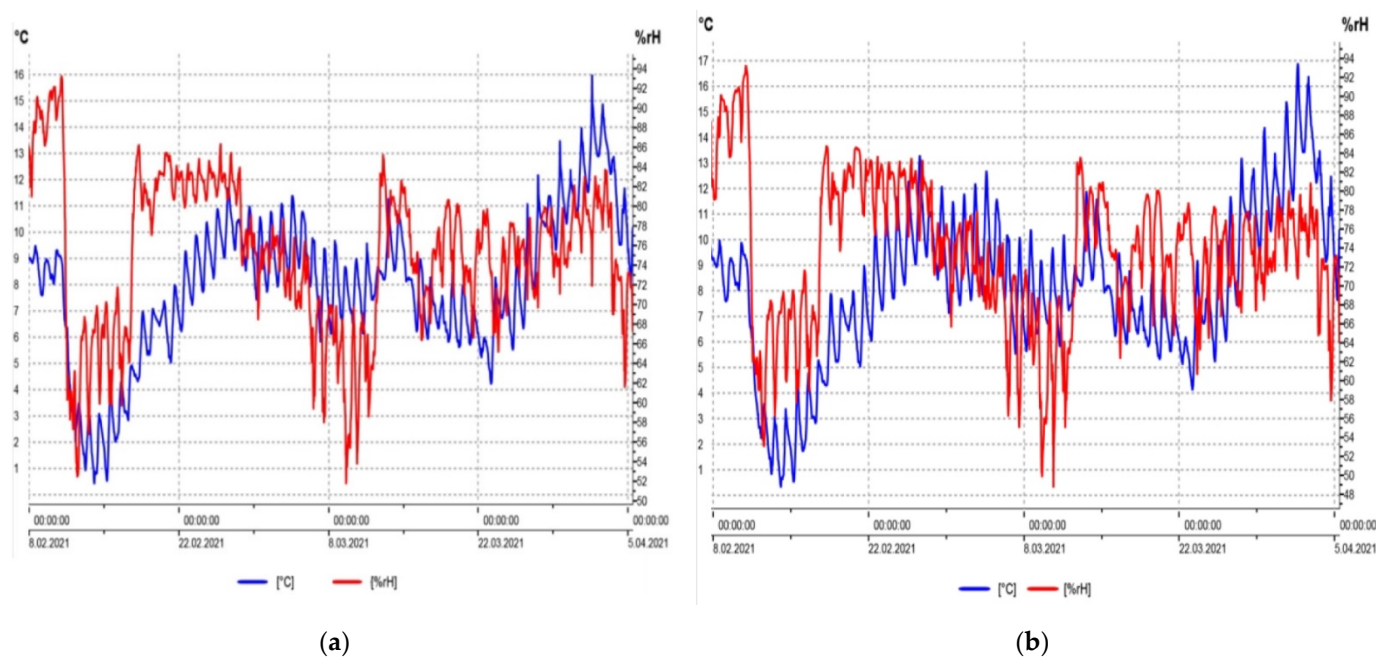


Figure 3. Graphic representation of temperature and relative air humidity inside the Visitor Centre of the Imperial Palace: (a) The values read from the data logger DL1 (placed at 30 cm above the floor mosaic); (b) The values read from the data logger DL2 (placed at 3.50 m above the floor mosaic). Source: A. Ugrinović and B. Sudimac.

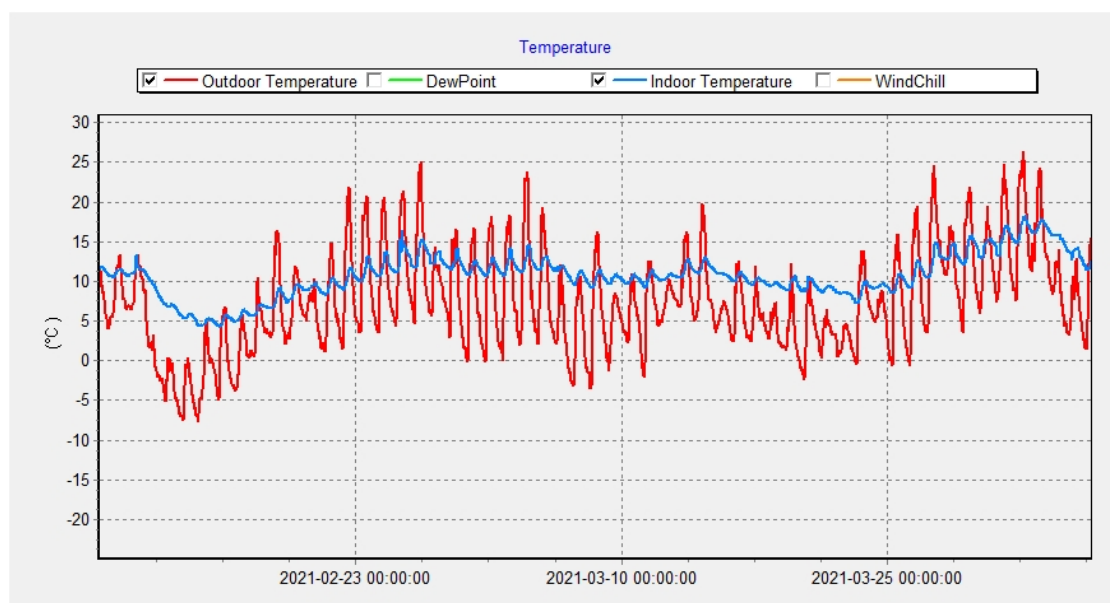


Figure 4. Graphic representation of temperature inside and outside the Imperial Palace Visitor Centre. Source: A. Ugrinović and B. Sudimac.

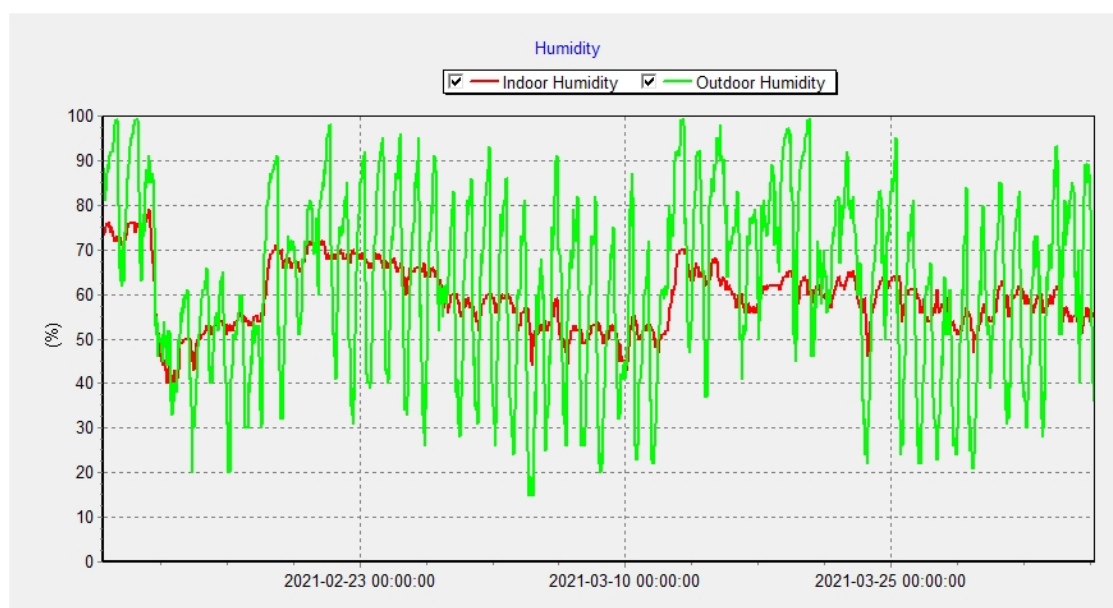


Figure 5. Graphic display of relative air humidity inside and outside the Imperial Palace Visitor Centre. Source: A. Ugrinović and B. Sudimac.

6.2. Biological Colonization of Mosaics

In situ optical microscopy provided better insight into the mosaic's surface. The stone surface was deteriorated with visible cracks and detached stone fragments (Figure 6). The M23 and M34 mosaics were intensively overgrown with mosses. Additionally, thalli of epilithic lichens were documented on the M2 mosaic.

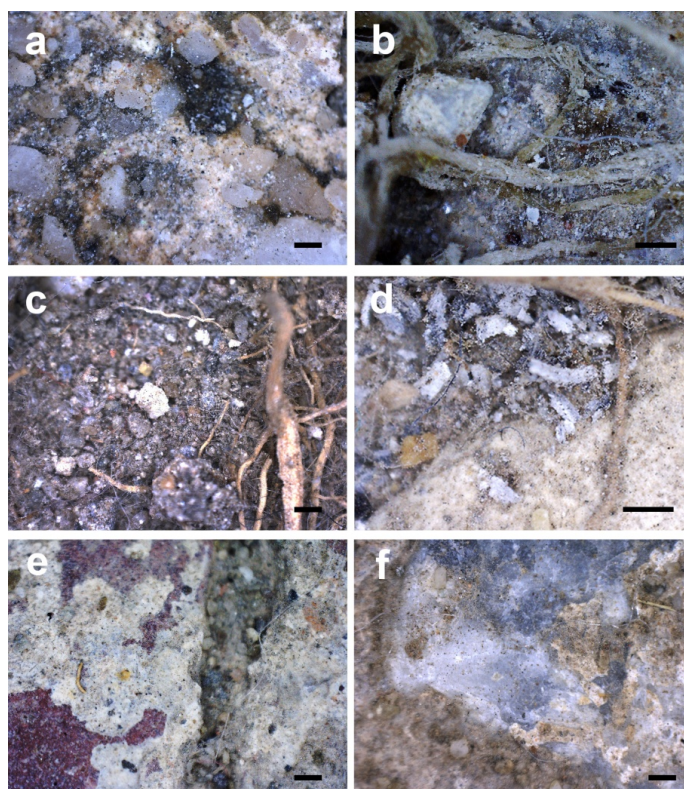


Figure 6. In situ optical microscopy of the deteriorated mosaics' surface with visible moss rhizoids and lichen thalli: (a,b) M23; (c,d) M34; (e,f) M2. Scale bar: 1 mm. Source: Ž. Savković.

The examination of the adhesive tapes revealed an abundant microbiological contamination of the M34 and M2 objects (Figure 7). Various types of fungal propagules were detected, most frequently melanized conidia of the *Alternaria*, *Cladosporium* and *Epicoicum* species along with unidentified dyctiospores, scolecospores, chlamydospores and ascospores. Additionally, various plant tissues, trichomes, pollen grains and green algae cells were detected along with occasional nematode specimens and hairs of animal origin. Conversely, the adhesive tape examination of the M23 object showed no visible microbiological structures.

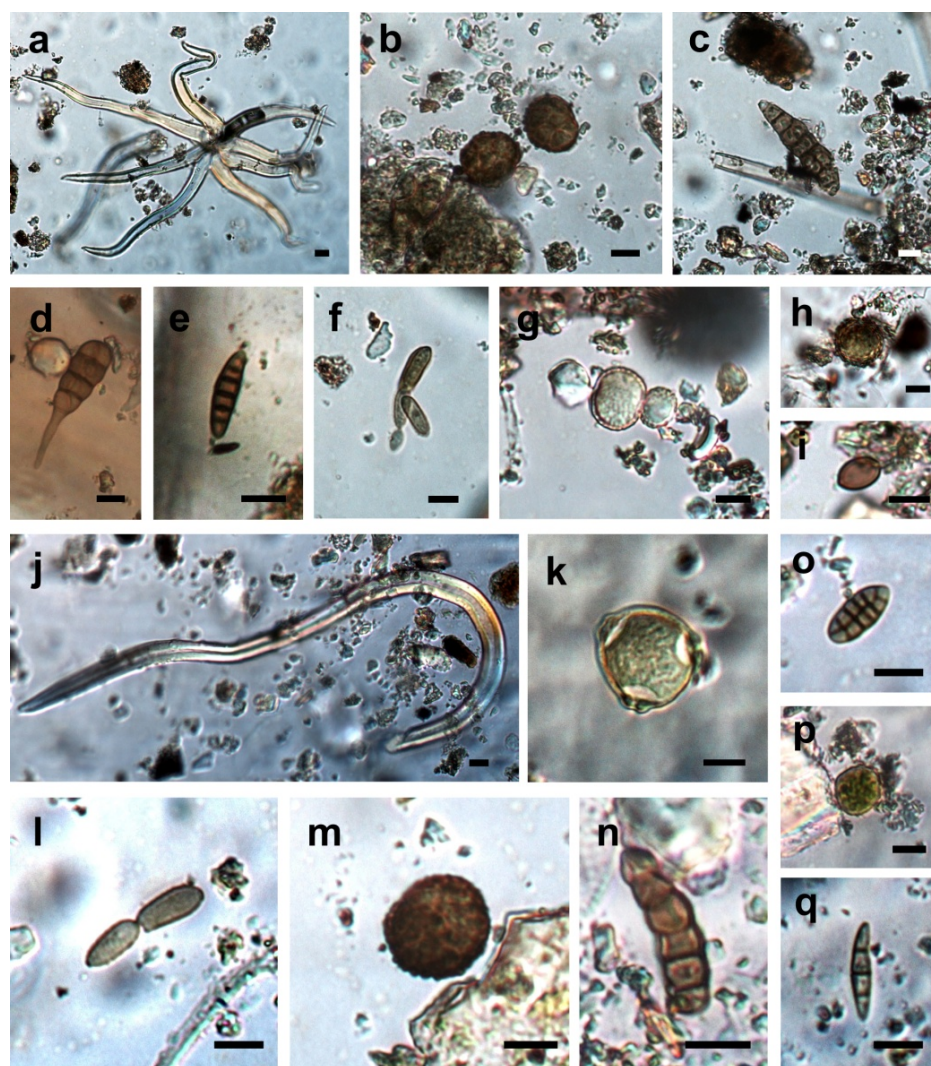


Figure 7. Biological structures detected on the mosaics' surface detected via adhesive tape (M34: (a–i); M2: (j–q)): (a) plant trichome; (b,m) *Epicoicum nigrum* conidia; (c,d) *Alternaria* spp. conidia; (e) melanized scolecospore; (f,l) *Cladosporium* spp. conidia; (g,h) chlamydospores; (i) ascospore; (j) nematode; (k) pollen grain; (o) melanized dyctiospore; (n,q) scolecospores; (p) green alga. Scale bar: 10 μ m. Source: Ž. Savković.

The sterile cotton swabs samples provided further insight into the composition of the viable microbiological community (Table 2). The lowest number of microorganisms was isolated from the M23 mosaic (only 40 CFU cm^{-2}), while the abundance of microorganisms on the M34 and M2 objects was significantly higher (164 CFU cm^{-2} and 208 CFU cm^{-2} , respectively). Bacteria were the most frequently cultivable microorganisms in all samples while fungi were represented by species of seven genera: *Alternaria*, *Aspergillus*, *Cladospo-*

rium, *Fusarium*, *Penicillium*, *Rhizopus* and *Scopulariopsis*. Among them, the *Cladosporium* and *Penicillium* species were most frequently present (Table 2).

Table 2. Fungi isolated from the investigated mosaics via sterile cotton swabs sampling. Source: Ž. Savković.

Sampling Site	Detected Taxa	CFU cm ⁻²
M23	<i>Penicillium</i> spp.	4
	<i>Fusarium</i> sp.	3
	<i>Alternaria</i> spp.	2
	<i>Scopulariopsis</i> sp.	1
	<i>Cladosporium</i> sp.	1
	Bacteria	29
M34	<i>Aspergillus niger</i>	3
	<i>Penicillium</i> spp.	3
	<i>Cladosporium</i> sp.	12
	Bacteria	142
M2	<i>Aspergillus niger</i>	2
	<i>Cladosporium</i> spp.	15
	<i>Rhizopus</i> sp.	1
	Bacteria	190

6.3. Airborne Microorganisms

Aerobiological sampling demonstrated 1572 CFU m⁻³ (equivalent to 30 colonies on a petri plate) at the sampling site adjacent to the M23 mosaic and 2883 CFU m⁻³ (equivalent to 55 colonies on a petri plate) adjacent to M34. Most of CFUs belonged to bacteria and only few *Cladosporium* colonies were documented.

7. Discussion

The results of microclimatic monitoring at the Visitor Center of the Archaeological Site 1a Sirmium Imperial Palace indicate that environmental conditions deviate from the recommended values of microclimatic parameters for the preservation of museum collections of the AICCM and from the document on persistence of hygroscopic materials published in the declaration of ICOM-CC and ICC [25]. During almost the entire measurement period, the relative air humidity was above the recommended value of 60%, with the greatest daily oscillations of up to 30%. The temperature was mostly below the recommended lower value of 15 °C, with the maximum daily variations of up to 6 °C. At the lower measurement positions, closer to the Imperial Palace floor mosaics remains, the relative humidity varied within the permitted range on 12 February, and from 6 to 12 March and on 4 April 2021, while a temperature above 15 °C was recorded as late as 1 April. It has been established that the relative air humidity values are lower at a greater height, i.e., at a greater distance from the elevation of the finds. Looking at the vertical distribution of relative air humidity and temperature, it transpires that the relative air humidity decreases while the temperature increases from the architectural remains of the Imperial Palace towards the roof structure of the Visitor Centre. In that manner, the interdependence of the relative air humidity and temperature has been confirmed.

Although the temperature in the Imperial Palace during the monitoring period was mostly below the recommended range according to ASHRAE [24] and the authorities in this area, it does not pose a problem because it has turned out that the artifacts exposed to lower temperatures are more stable. This does not slow down the natural aging of the finds. It should be noted that the temperature does not fall below 0 °C and the freeze–thaw

cycle is therefore avoided, and it is a known fact that these processes have an adverse effect on inorganic, porous hygroscopic materials that form the mosaic structure [7]. However, it should also be considered that low temperatures are not convenient for the visitors' stay.

A greater problem for the conservation of the finds is the high value of the relative air humidity and the large daily oscillations. The causes for such a high relative air humidity in the Visitor Centre should be sought mainly in the site conditions as well as in the applied materialisation and non-existence of natural ventilation, i.e., the possibility of airing the site. The proximity of the Sava River, the high level of ground waters and the presence of the Renney wells on the site may be the main reasons for the increased humidity.

Based on the results of microclimatic monitoring and in order to optimize the microclimatic regime and create conditions for the sustainable presentation and preservation of findings in situ, it is necessary to take certain corrective measures. Bearing in mind that the artifacts have adapted to their environment over the years and that any sudden change would be dangerous for their preservation, it is recommended to apply a dynamic model according to which microclimate optimization is achieved by passive measures, which are being increasingly applied in practice today [11,12]. The dynamic approach is based on slow changes in indoor microclimatic conditions, following seasonal changes in the outdoors. However, daily variations in the temperature and the relative air humidity must be within acceptable limits, i.e., it is necessary to maintain them in the recommended range in order to avoid the degradation processes of the material (± 4 °C, for hygroscopic materials, max. $\pm 10\%$). In order to regulate the microclimatic regime in the Visitor Centre of the Archaeological Site of the Imperial Palace Sirmium, it is recommended to replace the existing windows and install new ones with an opening mechanism, which would enable air exchange. This would contribute to the reduction of the relative humidity and to the faster elimination of suspended particles and microorganisms. Bearing in mind that the formation of microclimatic conditions in the Visitor Centre is conditioned by changes in the external microclimate, it is necessary to thermally insulate the building in order to slow down this process. By installing thermal insulation in the external walls and roof construction, the thermal characteristics of the building would be improved and thus heat gains in summer and losses in winter would be reduced.

The results of the microbiological analyses, the contamination degree of the mosaic and the presence of microorganisms in the air have ensured an insight into the current situation on the site in order to establish the biological deterioration hazard of the finds and assert the necessity to conserve the mosaics for preservation purposes. The applied microscopical techniques and cultivation methods showed a higher biological colonisation of the M2 and M34 mosaics compared to M23, which demonstrated lower CFU counts per surface, as well as adhesive tape examination. This can be attributed to the fact that M23 was recently cleaned during the conservation treatment and organic material from it removed. About 50 years have passed since the conservation of the M2 and M34 mosaics, and extensive contamination is expected. According to the current state, these mosaics need to be re-conserved. In situ optical microscopy has only recently begun to be used for the investigation of cultural heritage made of stone and is credited as a rapid and practical method for biological screening. Furthermore, it is considered to be a cost-effective tool that can perform high level analyses [42].

Stone substrata are considered oligotrophic environments, but nevertheless, aerial depositions and the presence of phototrophic organisms such as algae, cyanobacteria and lichens could enrich stone surfaces with the nutrients necessary for the development of heterotrophic microorganisms, i.e., bacteria and fungi [43]. The presence of various fungal propagules on the stone surface and isolates obtained via sterile swabs suggests potential biodeterioration action. Namely, fungi are able to deteriorate stone both mechanically and chemically. Mechanical deterioration is demonstrated by active hyphal growth and penetration. On the other hand, the chemical biodeterioration of mechanisms of stone include the secretion of acidic metabolites and the production of pigments [44,45]. Some of these alterations can lead to both structural and aesthetic changes to the monument and can

be irreversible [44,46]. It is also asserted that biodeterioration actions lead to the changes to the thermal-hygic properties of the stone [47]. Species of the genera *Aspergillus*, *Alternaria*, *Penicillium* and *Fusarium* are frequently detected on lithic substrata [43,48], which is in correspondence with our findings. Recent studies carried out on ancient Roman stela [42] and a Portuguese king's tomb [49] confirmed the presence of the mentioned taxa on limestone and also demonstrated the biodegradation potential of selected fungal isolates.

The concentration of airborne fungal propagules is dependent on different environmental factors such as temperature and relative air humidity, as well as the availability of nutrients [50,51]. The cumulative effects of these factors are complex, and it is generally hard to determine how individual factors contribute to the abundance of biological propagules in the air [51]. In the temperate regions, the maximum concentrations of fungal propagules are documented during summer and early autumn, i.e., seasons when the relative air humidity is higher [52]. These are the reasons why it is necessary to continue air sampling in other seasons of the year. To this day, there are no universally accepted standards for microbial air contamination. Some sources propose that values above 1000 CFU m⁻³ are considered as high [53] while others ascertain a threshold of 1000 CFU m⁻³ for bacteria and 3000 CFU m⁻³ for fungi [54]. Nevertheless, increased levels of airborne fungal propagules are considered to pose a threat to cultural heritage, especially in enclosed and semi-enclosed spaces [55]. Therefore, a systematic monitoring of air quality is essential on the cultural heritage premises.

8. Conclusions

After the conducted microclimatic and microbiological research, it has been confirmed that high values and large daily oscillations in relative air humidity are the key factors for the devastation of finds in the Visitor Centre of the Archaeological Site 1a Imperial Palace Sirmium. In order to improve the existing microclimatic conditions and ensure the sustainable use of the property, passive measures are recommended before all the upgrades of the thermal characteristics of the facility and provision of natural ventilation. The analysis of the passive measures' efficiency for improving the existing microclimatic regime is not the subject matter of this paper, and it will be the focus of the next research.

Examining the impact of the microclimatic conditions on the stability of the mosaics in the Visitor Centre of the Archaeological Site 1a Imperial Palace Sirmium is the starting point for establishing the optimal microclimatic regime both for the comfortable stay of visitors and for the conservation of the finds. Since the measurements were taken in a short period of time, in order to obtain an insight into the microclimatic regime in all the seasons of the year, it is necessary to continue the environmental microclimatic monitoring.

Having in mind that the microclimatic aspect has been neglected in the design of protective structures on archaeological sites, although it is an important factor in the conservation and preservation of the mosaics, a broader contribution of the research is based on the use of the research results as a starting point for the introduction of microclimate monitoring as a mandatory procedure inside protective structures, as well as in designing new solutions for the display of material finds.

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