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Original article

Characterization of airborne particulate matter and microbes inside cultural heritage collections

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ABSTRACT

Measurements of airborne particulate matter mass concentration, mass size distribution, chemical speciation and microbial levels were performed in two museums and a library in Greece over a two-year period. The three cultural heritage sites were located in different environments [coastal (Heraklion), urban (Athens) and mountainous (Zagori)], and their collections consist mainly of organic materials. Particulate mass size distribution measurements (PM_{10}) (cut-off diameters at 10, 9, 5.8, 4.7, 3.3, 2.1, 1.1, 0.7 and 0.4 μm) were performed inside the museums in conjunction with measurements of viable, cultivable microorganisms in air (heterotrophic bacteria, autotrophic chemolithotrophic bacteria, bacteria with metabolizing capabilities for exhibited organic materials, gelatin hydrolyzing bacteria, acid producing bacteria and fast growing fungi). The particulate matter measurements showed a variability, which was related to outdoor particle concentrations, indoor environmental conditions, infiltration rates and to indoor activities. The $PM_{2.1}$ fraction of the PM_{10} mass had a value close to 0.6 indicating a significant outdoor origin. Chemical analysis (ions, carbonaceous material and metals) of particulate matter revealed that ions and organic carbon comprised the major part of the particle mass. Elevated concentrations of Fe, Al-rich and soluble particles were measured indoors in the three sites. An enrichment of bacteria with metabolizing capabilities for bone, parchment, woolen fabric, gelatin, and cellulose was encountered indoors in the cultural heritage sites studied as well as inside closed showcases. An indication of seasonal variations of the airborne microbial load was observed in the three cultural heritage collections. In addition, there were differences in the measured microbial load, indoors, inside the showcases and outdoors.

1. Research aims

The present study focuses on the characterization of inhalable particulate matter and on the determination of viable, cultivable, airborne microbes, which can metabolize organic materials, exhibited indoors inside showcases and rooms, and outdoors. The chemical analysis of particulate matter includes the determination of ions, metals and elementary/organic carbon fractions in conjunction with source apportionment using enrichment factors. Seasonal measurements were conducted in the Historical Museum of Crete, Heraklion (coastal environment), the Criminal Museum of the University of Athens (urban environment) and the *Neofytos Doukas* Library, located in Zagori/Ioannina (mountainous environment) for a period of two years. Their collections consist mainly of organic materials, such as textile, leather, parchment, bones, wood and paper.

2. Introduction

Air pollution can have disastrous effects on cultural heritage monuments in both outdoor and indoor locations [1]. In the indoor environment, air pollutants penetrate from outdoors or are emitted from indoor activities and the building construction materials [2]. The interaction of the atmospheric environment with cultural heritage materials is complex. The atmosphere contains a mixture of gasses and particles including microorganisms and in several historical buildings and museums temperature, relative humidity

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and light conditions are not stable. Furthermore, cultural heritage items and especially those including organic materials, have undergone changes in their structure over time and are not interacting with the atmospheric environment in the same way as modern materials. Three main pathways for the degradation of materials can be summarized as physical, chemical and biological [1,3]. More precisely, environmental conditions, air pollutants and microbiological load affect the preservation of organic materials located in museums [1,2].

Particulate matter (PM) is considered as an important pollutant for the deterioration of cultural heritage materials in museums due to chemical reactions on surfaces and soiling [4–11]. The microbial load may also result in the destruction of organic materials in museums [10,12–17]. Some bacterial (e.g. *Streptomyces*, *Micrococcus*, *Bacillus*, *Kocuria*, *Staphylococcus*) and fungal strains (e.g. *Aspergillus*, *Penicillium*, *Alternaria*, *Rhizopus*) have been shown to destroy historical objects composed of organic materials [13,16,17]. Previous measurements of the seasonal variation of viable, cultivable airborne heterotrophic bacteria and fungi at the cultural heritage sites studied in this work, showed a considerable variability with the lowest concentrations of airborne microorganisms at the Historical Museum of Crete [10].

In this work, the particulate matter mass size distribution and chemical composition, as well as the concentration of airborne microorganisms with metabolizing capabilities for organic materials, was studied for a period of two years in two museums and a library in Greece.

3. Methodology

3.1. Sampling locations

Measurements were conducted for two years (March 2013–February 2015) in two museums and a library, located in Greece. The measurement sites have mainly organic exhibits (textile, parchment, bones, wood, paper, mummified tissues, etc.). Measurements were performed at:

- the Historical Museum of Crete located at a coastal environment in the city of Heraklion, with control of the microclimatic conditions (mechanical ventilation, artificial light) and a moderate number of visitors during the whole year (on average 500 visitors per month);
- the Criminology Museum of the University of Athens located in an urban environment, naturally ventilated with occasional use of air conditioning and low number of visitors (on average 20 visitors per month);
- the *Neophytos Doukas* Library located in a mountainous environment at Ano Pedina village of Zagori region at the Prefecture of Ioannina, naturally ventilated with occasional visitors (two persons per month to clean the room and on average 40 visitors per year) [10].

The measurements were performed indoors in the three museums. In the Historical Museum of Crete, the site was inside an ethnographic exhibition room of organic materials. In the Criminology Museum of the University of Athens, the sampling site was located in the centre of the exhibition room, whereas in the case of the Neophytos Doukas library the measurement site was located in the centre of the main library [10].

The measurement campaign included the monitoring of meteorological conditions (temperature, relative humidity and light) and the sampling of gaseous, particulate matter and bioaerosols. In the current study, the focus is on the particulate mass size distribution, chemical characterization and bioaerosol measurement characteristics.

3.2. Particulate matter – bioaerosol sampling

The measurement schedule for each site included a two days campaign every third month with the aim to examine the seasonal variability for a period of two years. Due to the limited number of samples per season, the measurements only indicate seasonal variations during the monitoring period. Gravimetric measurements were conducted with a 9-stage Andersen non-viable impactor (ACI, Thermo), in order to determine the PM_{10} mass size distribution. The samples were collected on quartz microfiber (QF) filters (Whatman Labware Products) for a period of 24 hours [18]. Before and after weighing, the filters were conditioned in a laboratory room with constant temperature (24 °C) and relative humidity (40%) for a 24-h period. For the weighing a Sartorius balance (Sartorius CP 225D, Sartorius AG, Goettingen, Germany) with mass resolution of 0.01 mg was used.

The collection of viable particles larger than 1.1 μm was performed using the MAS 100 one stage sampler (Merck, Germany) with flow rate of 100 L/min following a standard methodology [10,19]. The measurements in each cultural heritage collection occurred at three locations (indoors, inside closed showcases and outdoors) using two sequential repetitions on each specific growth medium in order to determine the indoor/outdoor relationships and the effectiveness of showcases in protecting organic exhibits. The collected air volume by the MAS 100 sampler varied from 50 to 250 L and was optimized so that the colony number per plate (90 mm diameter agar Petri dishes) did not exceed 80. Concerning the measurements in the showcases, the volume sampled was lower than the show case volume. However, due to sequential repetitions there was a mix with the air of the indoor environment during the sampling. Therefore, the results of the measurements in the showcases are indicative of the actual microbial concentrations.

The determination of viable, cultivable, airborne microbes was based on the cultivation of the air-collected microbes on microbiological growth media [10,19]. The autotrophic chemolithotrophic bacteria were cultivated in Minimum Mineral Tris Phosphate Agar [MTPA; Leibniz Institute DSMZ, No. 457 Mineral Medium (Brunner)] without any carbon source at 37 °C for 8 days. Bacteria capable of metabolizing the exhibited organic materials were grown in MMTPA with the addition of 5 g/L of one specific carbon source (cellulose, gelatin, leather, bone, or woolen fabric) at 37 °C for 8 days. Non-chemically pretreated bone and parchment were powdered before use, whereas woolen fabric was cut in microfilaments. The bone samples used were metapodials of modern deers (roe deers – *Capreolus*) from Denmark [20], whereas the fabric used was merino wool [21]. Parchment made from goat skin was supplied from the National Research and Development Institute for Textile and Leather (Bucharest, Romania). In addition, gelatin liquefying bacteria, possessing the ability to produce gelatinases, were cultivated in Nutrient Gelatin Medium (Difco Laboratories, Inc., USA) containing 1.5% of agar at 37 °C for 8 days. Gelatin liquefying bacteria counted only when gelatin was liquefied around and below the colonies. Uninoculated control plates that were incubated under the same conditions, were used for comparison. Highly purified agar (Merck, Germany) and ultra pure water were used for the preparation of all used growth media. The airborne concentration of microorganisms is presented as colony forming units per cubic meter (CFU/m^3).

3.3. Particulate matter chemical analysis

The procedure for the chemical analysis was described in detail by Kopanakis et al. [18]. Half of each filter was used for ICP-MS

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