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Assessment of Dust Deposition through Image Analysis in Complex and Remote Exhibition Sites: Study in the Cloister of the Santa María de El Paular Monastery in the Sierra de Guadarrama, Spain

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Abstract: Dust deposition is an important aspect of the conservation of heritage collections. Most proposed methods for dust monitoring focus on total area coverage or airborne concentrations. There is a lack of published data and methodologies to obtain size distributions of deposited particles on real historic sites. The purpose of the study was to develop and describe a method for obtaining quantitative data from dust deposition without the need for sophisticated laboratory equipment, based on optical microscopy photography and software-based image analysis. Bare microscope slides were used as passive collectors of dust. Tests were carried out on a collection of oil paintings displayed in the cloister of the Monastery of Santa María de El Paular in the Sierra de Guadarrama in Spain for one year, with a distance of 100 km between this place and the laboratory. The designed method allowed for the detection of significant differences in deposition depending on the location and seasonal period. Vertically orientated bare slides did not provide relevant information and a magnification of 50× was not really useful. However, horizontal collectors and a magnification of 10× allowed studying the deposition of particles above 2 μm^2.

Keywords: heritage science; image analysis; preventive conservation; ImageJ; coarse particles; air quality

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1. Introduction

Dust is a contaminant considered of capital importance in preventive conservation applied to indoor cultural heritage, although it is not sufficiently studied [1]. Dust deposition reduces the value of surfaces not only aesthetically, but also by promoting chemical deterioration [2,3]. Suspended dust is always present in exhibition and storage areas, unless they were specially designed to avoid its presence (clean rooms). Unfortunately, these types of spaces are not common in the field of cultural heritage collections, although it is possible to adopt different strategies to minimize the presence of airborne particles and their adverse effects.

There are different systematized methods for measuring the amount of particles suspended in indoor air [4], some of which have been applied to the conservation of cultural assets [5–8].

Without a doubt, the study of the nature and distribution of dust depositions is fundamental to the design of mitigation strategies, and this is something that was learned and applied early on, as demonstrated by Waite's 1896 article [9] regarding the deposition of dust inside museum display cases. This paper is also significant for two more reasons: it uses 'glass slips (...) to register any dust which might be deposited' and points to the help of magnification to study that deposition. All this makes him a pioneer of low-cost evaluation techniques based on image study.

Regarding the study of deposited dust, there is abundant literature on its study through scanning electron microscopy, energy dispersive X-ray analysis, chromatography analysis, and other analytical techniques applied to various fields [10], as well as in the field of heritage science [11,12], although these require very expensive equipment and facilities, which are normally beyond the possibilities of cultural institutions with limited resources such as small museums, small churches, monasteries, or other historical buildings.

There are also proposals aimed at satisfying the needs of these cultural institutions that seek low-cost and low-technology methods, which seem to be inspired by the line marked by Waite's pioneering study cited above. In the United Kingdom [13], the use of stickers and a simple visual inspection was recommended, and a booklet was produced for free distribution through the National Trust [14].

Another simple technique consists of letting the dust settle on glass plates (microscopy slides) and studying the variations in reflectance experienced by its surface, a magnitude that would be linked to the amount of dust deposited [15–17].

Allowing the dust to settle naturally on a glass slide for study using optical microscopy combined with digital photography and image processing techniques would still be considered a low-cost technique, which has been used for specific studies [18] and has been proposed to be used routinely in museums [19].

Image processing techniques have also been used to apply images of dust covering artistic objects in their display location [20]. The design of an experimental device based on a CMOS image sensor that automatically takes images of the powder that is deposited on it [21] undoubtedly follows the same trend, although it already represents another step in technological sophistication.

Although several monitoring methodologies have been published, the devil is in the details. There is still a lack of detailed and fully reproducible workflows that describe each step: the collection and transportation of samples, the image-taking strategy, and the processing. This article develops these aspects, which have not been treated in detail and together. To this end, it addresses the specific challenge of carrying out a campaign to collect dust samples deposited at a historical heritage site where large-format paintings are exhibited, and which lacks a laboratory and specialized personnel. The campaign lasted a full year. The main objective is to propose a viable, low-cost method, without the need for sophisticated equipment, which allows carrying out this type of campaign in places where cultural heritage is exhibited, from a laboratory that is not necessarily nearby.

This is a study that will help prepare similar monitoring campaigns. By doing this, it can significantly improve the care and conservation of many heritage collections.

2. Materials and Methods

2.1. Settings

The experiment was carried out at Santa María de El Paular Monastery, located in the mountainous environment of the Sierra de Guadarrama in the central part of Spain (40°53′19.0″ N 3°53′15.7″ W WGS84). A complete study of the monument and its surroundings can be consulted in a publication by Jiménez-Izarraraz [22], and a preventive conservation plan developed at the same site is available in another open publication [23].

Specifically, the study focused on the cloister of the monastery that houses an important collection of 52 oil paintings on canvas by Vincenzo Carducci, painted between 1626 and 1632. Dust samples were collected in the monastery for a full year, and they were later studied in the laboratory of the Institute of Spanish Cultural Heritage (IPCE). There was a road distance between them of approximately 100 km.

The cloister is closed to weather and has a gentle heating system that prevents temperatures below 10 °C in winter. There is a set of radio loggers that measure the relative humidity and temperature distributed throughout the premises. Specifically, there is one on the central part of each of its four sides. Furthermore, the State Meteorological Agency (Spanish: Agencia Estatal de Meteorología, AEMET) has a meteorological station on an exterior patio of the monastery, located 45 m north of the cloister.

The cloister has an approximate perimeter of 180 m. The paintings lack an exterior frame, with dimensions of (3.45 × 3.15 m), and their upper part is curved to adapt to the shape that the arches trace on the walls. In fact, the paintings were originally conceived for this space. Therefore, the upper part of each canvas is neither easily accessible nor suitable for holding a slide. Figure 1 shows a view of the interior of the cloister where the shape and arrangement of the Vincenzo Carducci canvases can be seen.

Figure 1. Shape and arrangement of the canvases in the cloister of the Santa María de El Paular Monastery.

The monastery is inhabited by a Benedictine monk community and is open for public visits 5 days a week.

2.2. Working Method

Glass slides were used as passive collectors, for which they were placed at seven different points (Figure 2). The central part of each side of the cloister (points 1, 3, 4, and 6 in Figure 2) was chosen as locations of interest, together with three other positions that could present peculiarities: next to a door that opened to the outside (point 2) (usually closed but used by the community of monks); next to the access door for cultural visits (point 5); and at a last point that is especially unfrequented (point 7).

It was impossible to establish collection periods of similar duration due to inclement weather, the COVID-19 pandemic, and bureaucratic problems. The collection periods were extended over a full year and are detailed in Table 1.

Table 1. Dust deposition periods between sample (slide) collection dates.

Placement Date	Collection Date	Days Passed
15 September 2021	21 October 2021	36
15 September 2021	15 December 2021	91
15 December 2021	21 January 2022	37
21 January 2022	10 March 2022	48
10 March 2022	12 May 2022	63
12 May 2022	30 June 2022	49
30 June 2022	28 July 2022	28
28 July 2022	1 September 2022	35

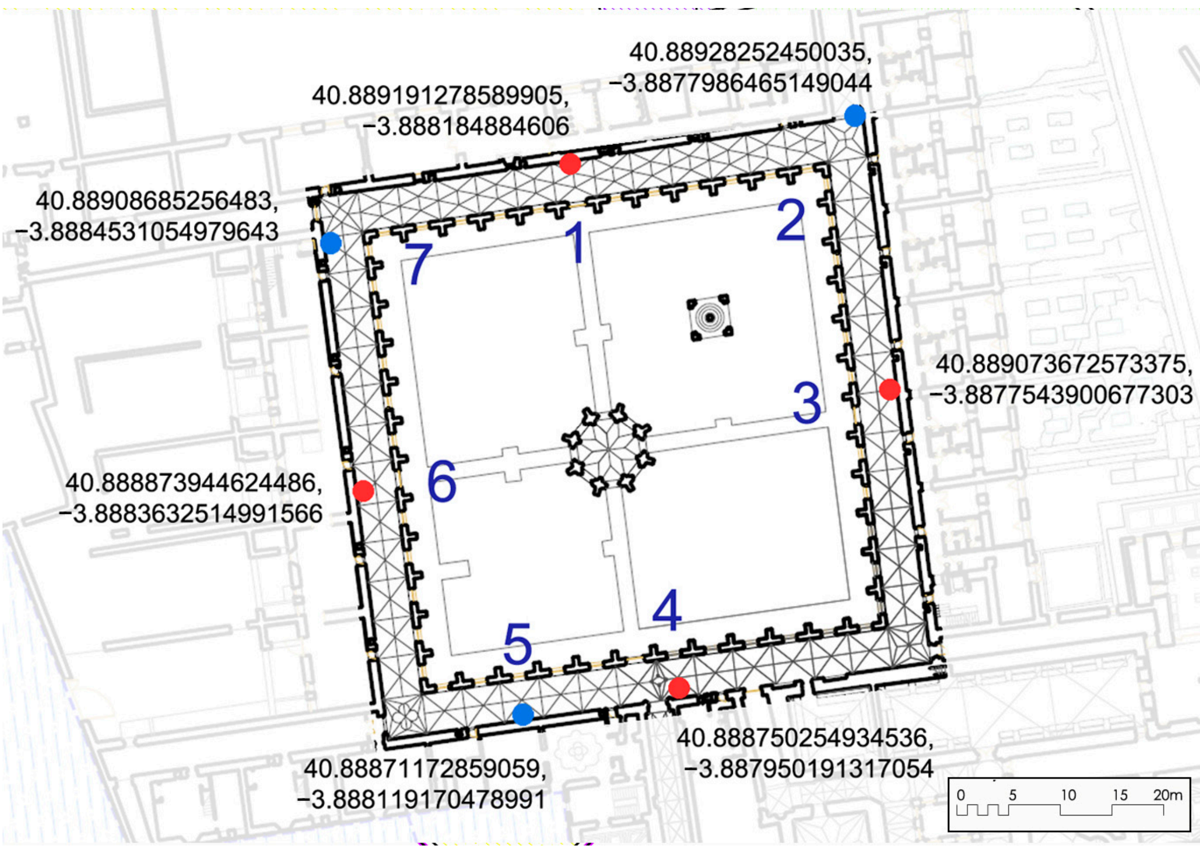

Figure 2. Location of the slides and how they were numbered. A red point represents a location at the center of an aisle, and a blue point represents another location of special interest. The coordinate system used is WGS84 (World Geodetic System 1984).

The general method followed these steps:

- Cleaning and preparation of new slides in the IPCE laboratory;
- Transfer to the monastery;
- Collection of the slides (samples) placed the previous time;
- Placement of the new slides;
- Transfer of samples to the IPCE laboratory;
- Photography (through a microscope);
- Image processing/data collection.

The avoidance of any kind of contamination during the transportation of slides was a critical point. To ensure that this did not occur, clean slides were used, which were transported together with those intended to receive the dust sample and checked after each collection session. There is a publication [10] that describes a method for 'the collection of settled dust in a form suitable for physical and chemical analysis', in which 'slides spiked with a known quantity of dust' were used in the same way to guarantee sample integrity. The conclusion was that the clean control slides presented a number of particles similar to that of the freshly cleaned slides: between 0 and 7 particles per image taken at 10x magnification, with 0 being the most frequent value. Since the average number of particles detected in the same way in the dust samples collected throughout the experiment was approximately 600 particles, the error attributable to both possible contamination during transport and poor cleaning was less than 1%.

Regarding the orientation of the slides, it was originally considered to place them all vertically (standing), since the aim was to study the possible deposition on the paintings hanging vertically on the wall. However, the first tests demonstrated the incorrectness of this decision: vertically placed slides were indistinguishable from the freshly washed slides when examined through a microscope. In other words, there was no significant and measurable dust deposition on them. Therefore, it was decided to redesign the experiment to use horizontally placed slides. However, the use of some vertical slides continued in order to confirm this trend.

2.3. Selection and Preparation of Slides

One of the first critical decisions was the choice of the manufacturer and model. For the first tests, commercial slides commonly acquired at the IPCE were used and their nonflatness was revealed as a major problem: the slides presented shallow depressions that prevented uniform focusing of all particles visible in the camera span; in addition, slides seemed slightly warped, so that with each necessary movement under the microscope objective for manual scanning, a blurring of the image occurred. Therefore, it was necessary to acquire new, higher-quality slides. Slides from the manufacturer Menzel Gläser were chosen according to the ISO 8037/1 standard [24] and prewashed and polished. They had a nominal thickness of 1 mm, a size of 76 × 26 mm, and 45º ground corners.

Despite this, two new problems emerged: when a slide was removed from its packaging bag and examined under a microscope, a large number of particles could be seen, despite the manufacturer's assurance that they were 'ready to use'. Furthermore, with the naked eye, in some of them, it was possible to detect some defects on the surface (when observed through the microscope, they were shown to be in the form of small polyhedral structures), possibly due to manufacturing defects or a hazing process during storage.

This made it necessary to take three precautionary measures: the systematic cleaning of the slides before their placement, discarding those slides with many defects (more than two, as it was decided), and recording (mapping) of the visible imperfections on the chosen slides, using free-hand sketches on a notebook so that the conflictive points that could lead to error could be avoided in the next steps.

Another critical point was not to produce scratches on the slides when cleaning them, to be able to apply automatic image processing later. For this reason, the usual cleaning procedures in the conservation of glass objects from heritage collections [25,26] were used, as they were considered the least aggressive, and their efficiency was verified through the microscope. In this way, the cleaning process was refined through trial and error until the following optimal procedure:

- Wash the slide under the tap with a minimum amount of neutral liquid soap. To do this, wet the slide, pour a drop of soap on a clean surface, touch the soap with the tip of a finger (hands covered with nitrile gloves), and spread the soap on both sides of the slide, rubbing gently. Rinse under the tap and repeat the rubbing and rinsing process until the soap has completely disappeared from both the finger and the glass;
- Hold the slide with tweezers and rinse it in a glass of demineralized water 5 times;
- Allow it to dry in the air, in a dust-free room without the traffic of people;
- Hold the slide with tweezers and rinse it in a glass with pure ethanol 5 times;
- Let it dry in the air;
- Place it in a cylindrical slide box (see Figure 3), which must have been previously cleaned with a light soapy solution of neutral pH and rinsed with water and pure ethanol.

The slides were numbered, although they were not written on to avoid dirtying them—the numbers were recorded on the outside of the slide boxes and in the before-mentioned notebook, instead. Finally, the final locations and orientations (horizontal or vertical) were noted, along with their numbers, in the same notebook after they were placed in the cloister, to ensure the traceability of the samples.

Figure 3. Cylindrical slide box used for transportation from the laboratory to the cloister.

2.4. Other Devices Used for Sample Transport

The transportation of the clean slides from the laboratory to the monastery was carried out using the aforementioned cylindrical slide boxes. However, the slides needed another type of box for the return journey to preserve the dust deposited: they had to keep a horizontal position and the container should minimize vibrations and be made of a material that could not 'steal' particles by electrostatic attraction. For this, hermetic glass storage boxes were used, similar to those that are usually used to store food in the refrigerator, with dimensions of 15 × 9 × 2.5 cm. Furthermore, separators were built with aluminum sheets approximately 80 µm thick to house 4 slides at the bottom of each box, to limit their movements and avoid contact between them (see Figure 4).

Figure 4. Hermetic glass storage boxes and aluminum separators used for sample collection and transportation from the cloister to the laboratory.

Of course, both the trays and the glass storage boxes were carefully washed and rinsed prior to every trip to the monastery. This packaging system also passed a rigorous test with a microscope inspection to verify that its contribution to the detected particles was zero or negligible.

2.5. Holders

Special holders were designed and manufactured to keep the slides vertically next to the canvases. Their fixation had to avoid drilling or the use of adhesives on the surface of the walls. The paintings lacked an exterior frame on which to adhere or nail, although they had stretcher bars. Furthermore, it was impossible to place the slides on the upper beam of the paintings because of their great height and curved shape. Finally, the device that can be seen in Figure 5 in its final version achieved all these requirements. The large plate on the right is designed to be inserted between the painting and the wall (a foam filler sheet could be used if necessary) so that the pressure exerted by the painting itself on the wall would hold the device. The first prototypes were made with folded, hardened, and painted bookbinding cardboard and were later replicated in sheet iron by a mechanical workshop after being successfully tested in the cloister itself.

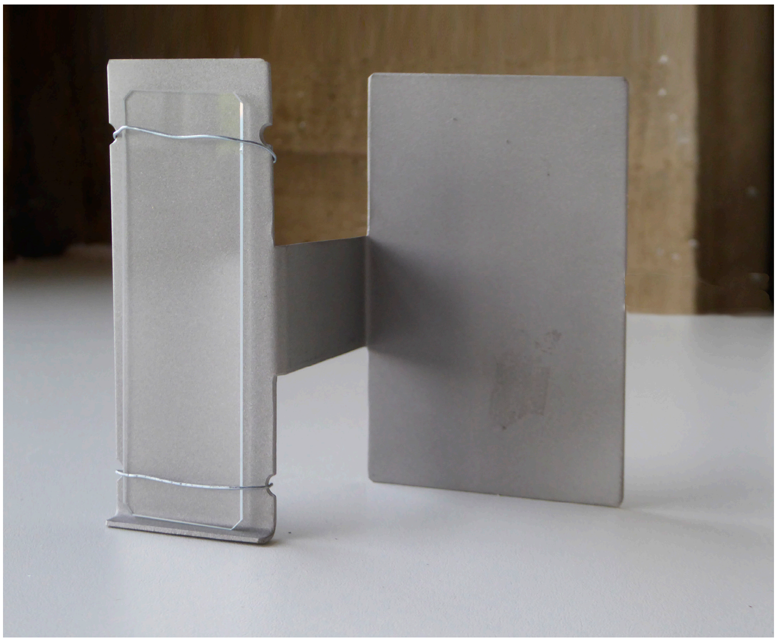

Figure 5. Final version of the vertical holder made of iron sheet. Note that there is a slide attached to it.

Other sets of holders were also designed and manufactured to place slides in a horizontal orientation. The result was the design in Figure 6, which follows the same principle of fastening to the wall. In this case, the cardboard binding prototypes were not made of metal, but were painted the same color as the walls of the cloister so that they would go as unnoticed as possible.

The vertical version requires two pieces of wire to tie the slide, while the horizontal version has a platform whose edges are slightly folded up to prevent the slide from falling. An additional precaution adopted for the horizontal version is the use of a second slide (of inferior quality) to serve as a barrier between the dust-collecting slide and the holder. Therefore, the upper slide was not contaminated with dirt that could accumulate on the horizontal surface of the holder.

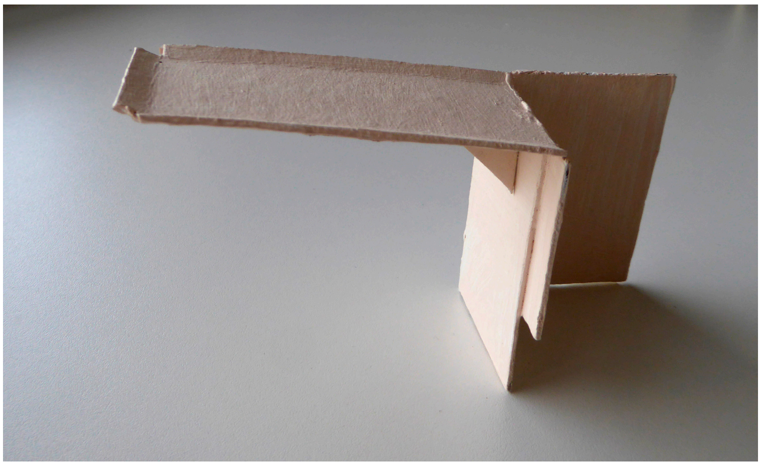

Figure 6. First and final version of the horizontal holder, made out of cardboard.

2.6. Placement and Collection of Samples

Both types of holders were located on the left side of the canvas at an approximate height of 3 m above the ground, with the vertical being 15 to 30 cm above the horizontal (Figure 7). Therefore, a step ladder was necessary to collect and replace the slides. The operation had to be carried out by two people, both using nitrile gloves and tweezers: one of them at the top of the ladder and the second helping from below.

Figure 7. Both types of holders located together. Note that the holders are held in place by the pressure of the bar stretchers of the canvas on the wall.

The first step was to remove the horizontal slide with the powder sample, with the help of tweezers, and immediately place it inside a clean glass jar, as seen in Figure 8, so it maintained horizontality and minimized contact with gloves and tweezers. The jar was handed to the second person (on firm ground), who carried it to the glass storage box, which had been left on the nearest windowsill. There, the location number (1 to 7) and orientation (H/V) were written on the slide with an indelible marker. The second horizontal slide (barrier) was then removed with fewer precautions.

Figure 8. Using a glass jar to minimize contact and keep the slide horizontal.

The vertical holder (when there was one) was removed entirely from the wall and replaced with another one carrying a new, clean slide. In fact, these slides were transported from the laboratory already tied to the vertical holders in a larger metal box. In this way, complex manipulations at the top of the ladder were avoided for safety reasons.

The next step was to place the inferior slide on the horizontal holder and place the other clean, higher-quality slide on top of it. The entire process was repeated until all seven locations were covered. The storage boxes were closed as they were completed (only four slides fit in each) and then wrapped in aluminum foil. The date was noted on the packaging, and the box was introduced in a plastic bag. The glass storage boxes were placed in a travel bag, secured with cushioning material (high-density expanded polystyrene plugs or similar materials), to be transported in the trunk of a car to the laboratory. Care was taken to ensure that the boxes remained horizontal throughout the process. This entire slide replacement operation took approximately two hours.

2.7. Sampling of Positions Established Prior to Taking Images

Three possible causes were foreseen by which the surface of the slides could be damaged or contaminated: microscope stage clips could scratch it, slide box rails and the aluminum separators could rub it, and both tweezers and gloves could add some particles. It was considered that this could mainly affect the ends of the slide (and to a lesser extent the longitudinal edges), so it was decided to discard the ends and only take images in the central longitudinal part (a portion of approximately 32 mm), as shown in Figure 9.

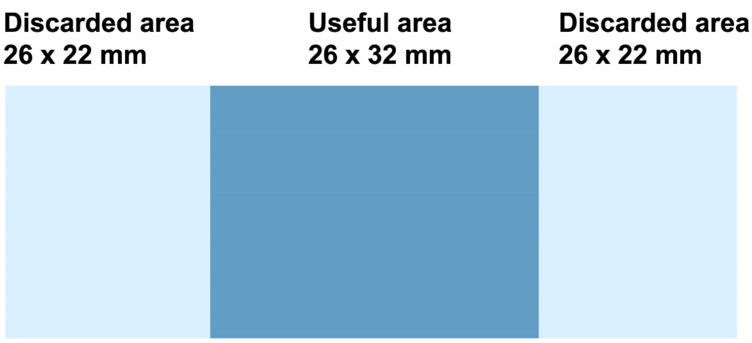

Figure 9. Section of the slides considered useful for photography (in darker color).

The number of images (samples) per slide was set at 40. A grid of 10 rows (longitudinal and numbered from 0 to 9) by four columns (transverse and named with letters) was established to code the positions on the useful surface. Each of the crossing points was coded by combining the number and letters of the corresponding row and column, as shown in Figure 10. The photographs were taken by manually pointing the microscope objective at these crossing points, so these were approximate (not exact) positions.

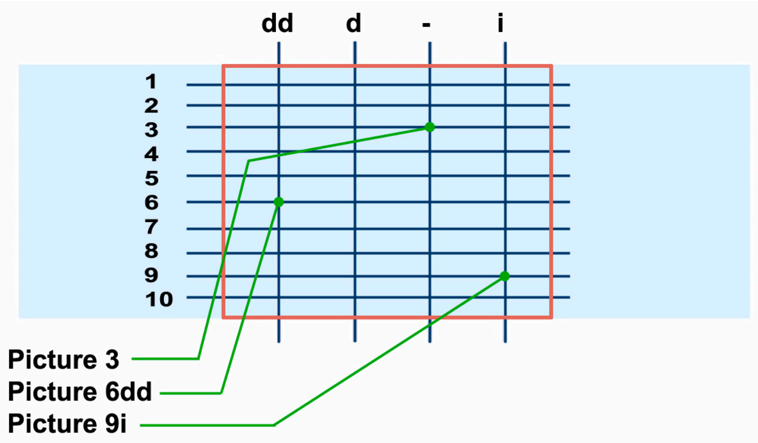

Figure 10. Grid and coding used to approximately mark the points to be photographed on each slide (40 photographs per slide).

During the first tests, the coding of the positions served to check if there was a correlation between the number of particles detected in each shot and their distance from the longitudinal edges, or, from another point of view, to determine which portion of the longitudinal edges should be discarded. The final conclusion was that the dirt at the longitudinal edges was concentrated in a margin of only about 10 µm, which was also discarded.

2.8. Photo-Shooting

An Olympus model BX51 optical microscope with a transmitted light source was used. Images were taken with an Olympus DP 25 camera integrated into the microscope itself and the cellSens imaging application. Initially, the samples were photographed at a magnification of 10× and 50×. Less than 10× was not feasible because particles deposited on the front and back of the slide appeared in the images, 10× had the advantage of covering the largest area per photograph, and 50× was the option reported in [20].

The equipment used did not allow for a complete systematization of the adjustments. The light source was adjustable, but it lacked a graduated wheel to repeat the adjustment. Something similar happened with the polarizing filter of the microscope. Therefore, the settings were different in each photo session. Furthermore, the contrast of the images changed each time the magnification number was changed (10× or 50×), forcing the settings to be changed even within the same session. The fact that the photographs were taken by two people with different criteria did not help in this regard. Thus, different exposure times, contrast settings, degrees of polarization, light intensities, etc. were taken throughout the series studied.

When the experiment was very advanced (75% of the images already taken), in one of the series of photographs taken at 50× magnification, a disconcerting correlation between the position within each image and the density of particles present was discovered: in the upper left corner there was always a noticeably higher concentration. It was concluded that some of these particles were not real but were superficial defects on the glass slide, only visible for certain polarization and gamma correction settings. The fact that they only appeared in the upper left corner was due to the lack of uniformity of the lighting. In fact, it was possible to adjust these settings to view these superficial defects all over the whole span of the microscope. Unfortunately, they were indistinguishable from dust particles because they were similar in size and shape. Fortunately, though, this phenomenon did not occur when using a magnification factor of 10×. At that time, it was already impossible to repeat the images taken at 50× magnification because many of the slides already photographed had not been preserved or had not been properly protected when stored. Therefore, there was no option but to discard all images taken at a magnification of 50×.

In any case, working at 50× magnification posed other drawbacks. First, the image was noticeably out of focus between shots more frequently; in fact, it was necessary to refocus (manually) 4 times more frequently, which tripled the time needed to make a complete scan. In addition, the lack of flatness of the slides was evidenced by the appearance of focused and out-of-focus points in the same image at the same time.

Additionally, the images were taken in TIFF format (Tag Image File Format), with dimensions of 2560 × 1920 pixels and an approximate weight of 14 Mb. The total number of valid images taken by each slide for each deposition period did not always reach 40, as some had to be discarded. There were three main reasons for discarding: the presence of large lint or fibers that appeared partly out of focus and obscured other smaller particles; compact depositions that occupied more than 1/3 of the image; and imperfections on the surface of the slide. Only 5% of the images taken at 10× magnification were estimated to be rejected.

In practice, photo-shooting has resulted in a time-consuming process because a photographic scan of the slide surface must be made, which involves moving it manually under the microscope lens. This lack of automation creates a trade-off between time spent and representativeness of the result, since the greater the number of images taken in that scan, the more representative the result will be. In our case, using a magnification of 10×, it takes half an hour to cover the useful surface of a slide when 40 images are taken. Any improvement in the automation of this process would be of great help in conducting these types of studies.

As for precision, the size of the area covered by each image obtained (10× magnification) with the equipment used is 0.869 × 0.652 mm, that is, 0.567 mm^2. Since the useful area of each slide was set at 34 × 26 mm, that is, 884 mm^2, the size of the sample space (or the number of images that would be necessary to cover the whole useful surface on a slide) is as follows:

$$U = 884/0.567 = 1559.$$

However, our sample is limited to only 40 images per slide (maximum). This is:

$$S = 40.$$

This means that the representability (or even the repetitiveness) of the results obtained will be highly conditioned by the uniformity with which the particles are deposited on the surface of the slide. However, there is no reason to think that this is not the case for particles of the sizes studied.

2.9. Image Processing

ImageJ software (version 1.51, released in April 2018) was used for image processing. ImageJ is an open-source software for processing and analyzing scientific images [27]. A specific workflow was developed.

The images, when obtained as previously described, are perceived as a set of dark particles that stand out against a light background. The processing applied to these images, broadly speaking, followed the following steps:

- Inversion of the image so that the background becomes dark and the particles become light;
- Conversion to an 8-bit black-and-white format;
- Application of an automatic threshold that assigns black pixels to the part of the image that is considered background, and white pixels to the areas occupied by a particle;
- Automatic measurement and counting of all particles in the image.

The result for each image was a comma-separated values (CSV) file that contained a list of all detected particles (numbered according to their position) and their size in μm^2.

Given the aforementioned disparity in image-taking settings, applying the same detection threshold to all images was ruled out. On the contrary, it was decided to calculate a threshold adapted to the characteristics of each image. For this, the auto-threshold plugin available in ImageJ [28] was used. Within this plugin, different options are offered (thresholding algorithms) to calculate the optimal threshold, so all of them were previously tested on different images, trying to cover different dates, different adjustments, and a variety of particle sizes.

The first results forced us to rethink and modify the aforementioned four-step workflow. The reason was that all the thresholding algorithms generated a large number of false particles in the darkest areas of the image, a consequence of the problem of lack of uniformity of the lighting on the spam of the microscope mentioned above. To cope with this, each image was divided into nine equally sized portions. In this way, the illumination gradient in each portion was much smaller, which allowed the application of some types of automatic thresholds successfully. After testing all the options available in ImageJ, the 'Triangle White' method [29] was finally chosen, because it was one of those that allowed the detection of all particles visible to the naked eye and limited the size of false results at very low values. Specifically, the size of all false results was always below two μm^2. Therefore, this value was taken as the minimum detectable particle, which means that the method presented in this paper would only be applicable in the range of the so-called coarse particles [30].

Therefore, two macros were written using the batch processing possibilities offered by ImageJ [31] to automate the process: the first, to divide all the images taken into nine; the second, to apply the image processing described above to each image. All of this gives rise to the following outcomes for each image taken: the nine image portions (9 files), nine images resulting from applying the threshold to each portion (9), and the other nine files in (CSV) format with the result of the particle counts (9).

The final workflow is shown in Figure 11.

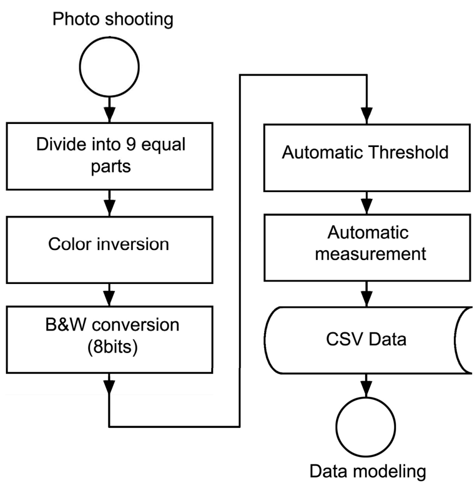

Figure 11. Image-processing workflow.

An example of an image taken through the microscope with 10× magnification (actually one of the nine parts into which it was divided), together with the result of applying the 'Triangle White' threshold and the diagram with the particles detected in it is shown in Figure 12.

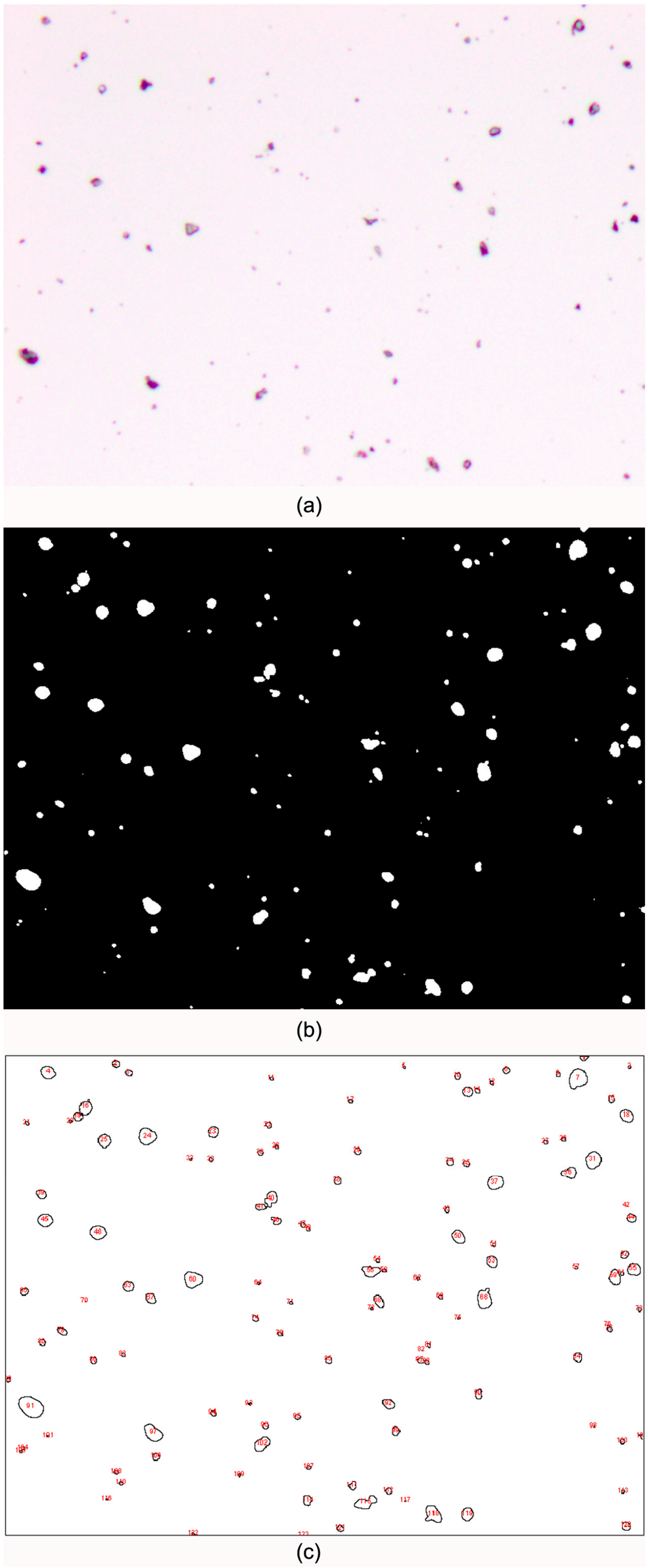

Figure 12. Image-processing example: (**a**) ninth part of an image taken with 10× magnification; (**b**) the same picture after applying threshold; (**c**) outline with the contour and numbering assigned to the detected particles (123 particles in total).

3. Results

More than 1,250,000 particles were detected in the 51 slides that were placed horizontally. The measurements show a wide variability of area per particle, with minimums below 1 μm^2 and maximums in the range of 10^5 μm^2.

Looking at the 50th percentile of the observations, we find that this statistic has, for the 51 samples, a minimum of 2.30 μm^2 and a maximum of 9.67 μm^2, which indicates that the majority of the particles collected are between 2 and 10 μm^2 in size. The 95th percentile of the area of each of the samples does not exceed the values of 10^3 μm^2 in any case.

A selection of these results can be seen in the graphs in Figure 13. In each of the graphs represented, the probability density function has been elaborated from the data of the 40 original images taken from a single slide. In addition, the decimal logarithm of the area (in μm^2) was used to improve the visualization of the data. Three different positions (1, 3, and 6—see Figure 2) have been taken with collection periods inserted in four different seasons: from 15 September 2021 to 21 October 2021 (autumn), from 15 December 2021 to 21 January 2022 (winter), from 10 March 2022 to 12 May 2022 (spring), and from 28 July 2022 to 1 September 2022 (summer).

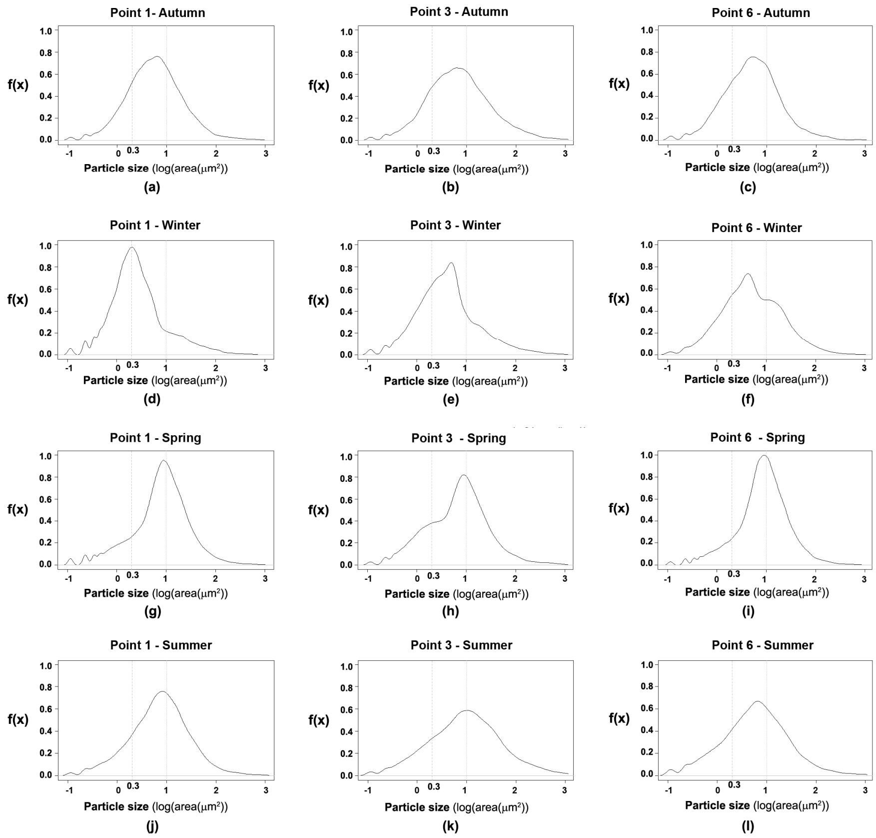

Figure 13. Examples of the probability density function (pdf) of particles detected at three different points during four different collection periods: (**a**) pdf of slide placed at position 1 from 15 September 2021 to 21 October 2021 (autumn); (**b**) ditto position 3 from 15 September 2021 to 21 October 2021 (autumn); (**c**) ditto position 6 from 15 September 2021 to 21 October 2021 (autumn); (**d**) ditto position 1 15 December 2021 to 21 January 2022 (winter); (**e**) ditto position 3 15 December 2021 to 21 January 2022 (winter); (**f**) ditto position 6 from 15 December 2021 to 21 January 2022 (winter); (**g**) ditto position 1 from 10 March 2022 to 12 May 2022 (spring); (**h**) ditto position 3 from 10 March 2022 to 12 May 2022 (spring); (**i**) ditto position 6 from 10 March 2022 to 12 May 2022 (spring); (**j**) ditto position 1 from 28 July 2022 to 1 September 2022 (summer); (**k**) ditto position 3 from 28 July 2022 to 1 September 2022 (summer); (**l**) ditto position 6 from 28 July 2022 to 1 September 2022 (summer). There is a mark with a value of 0.3 on the *x*-axis because it is the limit of the estimated precision.

In the winter collection, notable differences can be seen with respect to the others: the mode of the size of the deposited dust is between 2 and 10 μm^2 (0.3 and 1 when expressed as the decimal logarithm on the abscissa axis), while in the rest of the graphs represented, the mode is close to, or even exceeding, 10 μm^2. Also, in this collection period, notable asymmetries can be seen in the shape of the distribution, probably due to the collection of two different sources of dust, one of them larger than the other.

In the spring dust collection, distributions are clearly concentrated around 10 μm^2 (1 when expressed as the decimal logarithm on the abscissa axis), with the asymmetry of point 3 standing out. As can be seen in Figure 2, point 3 is close to a space aligned with a gate (see Figure 2), a circumstance that very possibly influenced it.

The graphs corresponding to the summer dust collection and the spring collection appear centered around 10 μm^2. In these distributions, there is also a widening at the base, showing an increase in the dispersion of the data. This increase in dispersion would be linked with a new seasonal cycle and with the autumn collection period, in which a shift to the left of the modal values of the three points can be seen, denoting a decrease in the average size of the particles from summer to autumn and also, as mentioned, from autumn to winter. The transition from winter to spring is seen with the appearance of submaximal values in the function and the increase in the modal values, as mentioned before.

These results allow us to establish hypotheses that can be confirmed or refuted with a more in-depth analysis linked to correlations with other variables (public attendance, incidence of meteorological phenomena such as wind, etc.) and deposition models, all of which will be the subject of a future publication.

4. Discussion

The main objective of this article is to present a low-cost method to carry out evaluations of dust deposited in spaces containing heritage collections. There are no sufficiently similar studies to allow comparison of results. However, in the scientific literature, one can find methods proposed for similar situations with which the method proposed here can be compared.

Methods based on measuring the variation of reflectance [15–17] have the advantage of allowing in situ measurements, but they provide a parameter that limits the possibility of analysis. However, taking images by optical microscopy and their subsequent processing allows for an analysis of the total covered surface (correlated with the variation of reflectance [15]) and, in addition, a more in-depth study through aspects such as the count of particles, area fraction, and particle size distribution [19], as well as enabling the use of advanced AI techniques to 'address the problem of shape recognition and classification of individual dust elements' [21].

Regarding methods based on taking photographs through an optical microscope, there are variations in the way dust is captured. Several of them use some type of gel or adhesive film:

- Ref. [19]: used 'dust lifter', which is a sticky gelatin film, to extract the dust sample from a glass slide before transportation;
- Ref. [15]: used sticky films ('Sticky Pads') to allow dust to settle on them. These samples were adhered to the back of several slides to be studied by optical microscopy;
- Ref. [18]: allowed the powder to settle directly on the slide and then covered it with an adhesive film, GelLifter©, before transport.

This use of adhesive tapes and gels carries the possibility of introducing some granularity or background texture that could be mistaken for a multitude of small particles when using software for automatic detection and counting. Furthermore, its use implies that the sample must be photographed through the thickness of the glass of the slide [15] or the film itself [18]; therefore, a significant loss of sharpness in the images taken is inevitable.

There was no loss of sharpness in the images taken in [19] from dust lifters, although some background graining is evident. However, in this case, it is worth asking: To what extent is the particle transfer complete? Are there losses? Is it possible to quantify these losses?

Therefore, the possibility of resorting to the direct use of slides is especially attractive. This is the option followed in the method proposed in this article but is only mentioned in one previous paper [20], in which direct deposition on the slides is used to then take images in situ with a microscope. In this same experiment, the dust deposited directly on the artistic objects was photographed. Despite the similarity, it represents a strategy opposite to that defended in this work: a mobile laboratory was moved or installed at the study site, instead of moving the samples to the laboratory.

The reluctance to transport glass slides without protection is evident. This option only was adopted in one paper [15], although the slides were intended for the study of the variation of reflectance. However, in this same study, a strong correlation was established between the result obtained through image analysis (in terms of 'fractional area covered') and the 'percentage loss of reflectance' ($r^2 = 0.91$), which reinforces the idea that it can be done successfully. In fact, the only transport precaution mentioned was the use of slide boxes with 'tightly fitting lids'.

Regarding transport without protective film or adhesive, there are two risks: contamination of the sample and loss of the sample. The first was avoided in this experiment (as discussed in Section 2.2. Working method) by using and testing extra clean slides during transport. The second is very difficult to evaluate, but it would be an interesting question to delve into in subsequent studies.

Regarding image-taking and image-processing, in two of the studies [19,20], the same image-processing program, ImageJ, which is proposed in this paper, was used. It is a very widespread software among the scientific community and has a very precise automatic particle counting function ('Analyze Particles'), which is the key to all three methods. Unfortunately, in these two references, there is no detailed description of the workflow for the treatment of the images obtained from the slides (Ref. [20] offers it for the images taken on the objects), nor precise indications on how the scans were carried out when taking images. On the contrary, these aspects have been developed in the description of the method proposed in this paper.

5. Conclusions

This article presents a detailed method for dust assessment in remote indoor environments housing heritage collections. It is a low-cost, low-tech method, based on taking samples of dust on bare slides to be photographed through an optical microscope.

A case study was carried out in the main cloister of the Monastery of El Paular in Madrid (Spain), which preserves a collection of 16th-century Carducci canvases, during a year.

Vertically placed glass slides had proven ineffective. Bare slides have proven to be a feasible option for settling and carrying dust, as long as they are kept in a horizontal position.

A workflow for semi-automated image processing has been developed.

Around 18,000 images have been processed during the course of the experiment and around 1,250,000 deposited dust particles have been counted, the majority between 2 and 10 μm^2. This has allowed us to characterize the probability density functions that show different seasonal behaviors according to different locations.

Knowledge of these behaviors is important to establish preventive conservation strategies to mitigate the adverse effects of dust in heritage collections.

The flatness of the slides is critical in determining the possible magnifications at which photographs can be taken, to the point of forcing the discarding of images taken at 50× magnification.

Photo-shooting is a time-consuming process, but 40 photographs per slide taken with a magnification of 10× represent a good compromise between time consumed and volume of data obtained.

The importance of this method lies in the fact that it opens the possibility of monitoring a harmful parameter such as dust deposition in a large number of heritage collections that do not have specialized personnel.

During the experiment, measurements of relative humidity and temperature were recorded inside, and measurements of meteorological parameters were recorded outside. There is also daily data on visitors to the monument and its occupancy level. In addition, other related data of interest is available, such as extreme meteorological incidents—the haze, for example, reported by the state meteorological agency. All this opens the possibility of seeking correlations between the results obtained and these other parameters to develop, or even test, mathematical or numerical deposition models, as a future line of research.

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