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Microblasting of powdered lignocellulosic particles: Cleaning of a wooden joint cover of a medieval coffered ceiling

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ABSTRACT

Mechanical methods used for cleaning unpolychromed wooden heritage in conservation-restoration rely on procedures that entail pressure and friction, potentially leading to erosion or material loss on the treated surface. In addition, certain methods, such as the use of sponges or erasers, very often leave residues that could affect the long-term conservation of wood due to their chemical composition.

The aim of this work is to assess the feasibility of using microblasting with powdered lignocellulosic particles for cleaning unpolychromed wood on a heritage artwork. The investigation aims to evaluate the advantages and drawbacks of this technique as a sensitive and sustainable alternative to the most common techniques used by conservator-restorers for unpolychromed wood cleaning. The cleaning results of microblasting of lignocellulosic particles are qualitatively compared to those achieved by traditional dry-cleaning techniques on wood.

This study is based on previous research that examined the effects of this technique on non-heritage wooden samples using hazelnut and almond shells, cork and pure cellulose powdered particles. The investigation aimed to assess potential morphological surface changes and to determine the degree of cleaning qualitatively without causing damage to the wood surface. Additionally, the study allowed the development of a cleaning protocol by selecting the specific particle size, and by adjusting pressure, angle, distance and time to surface soiling characteristics and wood typology according to the limited bibliographic references available.

From these results, tests were conducted on the back side of a wooden joint cover dating back to between the 14th and 16th centuries from one of the ceilings of the Monastery of Santa María de Pedralbes. The joint cover was weakened and affected by fungi and woodworm after centuries of outdoor climate exposure.

To evaluate the cleaning efficiency and the resulting effects on wood, the surface was analysed by digital optical microscopy and scanning electron microscopy before and after cleaning. Star diagrams were also made to assess the fulfilment of the cleaning criteria selected for the study.

Results indicate that when the technique is applied properly, an appropriate cleaning level can be achieved without compromising the fragile treated surface and with negligible presence of residues. Therefore, this approach emerges as a promising and environmentally friendly technique, respectful to the integrity of the heritage wooden artworks.

1. Introduction

Wood has been extensively used for centuries as a natural resource and it is found in cultural heritage collections in the form of everyday objects and ornamental items, artifacts, movable and immovable elements, painting frames and stretchers, sculptures, tables and altarpieces, wooden ceilings, ships and boats, carriages,

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domestic utensils and tools, and many other types of goods that make up the cultural heritage which is found everywhere and in all civilizations. It is found in both small-format objects and large-scale items. As a constituent material of cultural heritage, wood has historically been subjected to repair, maintenance, and conservation-restoration treatments, such as cleaning.

For cultural heritage cleaning, when wood is covered with a decorative finishing or, especially, polychromy, the decorative technique and pictorial materials determine the cleaning technique to be carried out. However, when wood is not polychromed or has no decorative finish —either because it never had one or it is not designed to be seen, as in the case of most of the reverse sides, or it has lost its polychromy— the cleaning system of the adhered soiling of these wooden areas is not usually documented in the conservation-restoration reports. This fact means that the cleaning intervention is undocumented, relegating the cleaning of unpolychromed wood to a lesser level of conservation-restoration intervention, as if it were not part of it [1].

The parts of cultural heritage made with unfinished, unpolished, or untreated wood because they were not meant to be seen, often have a great documentary interest because they show important data of the manufacturing process and the technology used.

In most cases, tool marks, fixing systems, angles and joints of pieces to create architectural features or sculptural volumes, indications of assembly determining whether the object was made up of parts, guild or authorship marks, and even sketches of parts of the same object, graffiti from workers or dates of old repairs can also be seen. All the above document the history of the object. To sum up, the reverse sides of wooden objects are an important document of their history and the technology of the time in which they were made [2,3].

For this reason, the cleaning of unpolychromed heritage wood areas, contrary to what usually happens, must be approached as a process of discovery and interpretation, which must be "read" and transcribed for the history of the object. In some cases, the information obtained may be the key to understanding the object and its context.

In addition to the documentary interest of unpolychromed areas, it should be noted that they are particularly vulnerable to biodeterioration. There are two main reasons for this; on the one hand, because they are not covered by a preparation and a pictorial layer leaving wood bare and exposed to biodeterioration agents; on the other, because they are often not easily accessible for inspection and preventive maintenance, as they remain hidden.

At the same time, wood is a natural and biodegradable material, both in nature and as part of cultural heritage. Its biodeterioration is a process that depends mainly on the intrinsic resistance of each wood species but is closely linked to conservation and environmental conditions, and it occurs inevitably over a greater or lesser length of time [4].

Both in the natural environment and as part of cultural heritage, biodeterioration begins chemically by the action of bacteria and fungi, and accelerates with the subsequent participation of xylophagous insects, which consume the physical decomposition of wood [5].

In all chemical biodeterioration processes —caused by the enzymatic action of bacteria and fungi— the cellulose, hemicellulose, and lignin molecular chains break, resulting in the degradation of the wood's cell walls, leading to fibre breakage and loss of wood mechanical resistance [6].

In physical biodeterioration processes —caused by xylophagous insects— the visible damage to the wood is mainly the proliferation of holes and galleries made by larvae that have fed on the wood during their growth.

In both chemical and physical degradation processes, wood gradually suffers loss of hardness, density, or mechanical resistance, affecting its physical condition. This process has various consequences, but regarding conservation-restoration treatments such as cleaning, the loss of inherent properties make wood as fragile and delicate as other materials composed of cellulose, hemicellulose, and lignin, such as cardboard or paper. Cleaning such a fragile tridimensional structure requires a cleaning system which can be strong enough to remove adhered soiling but also to respect the fragile wood under it.

Two main categories, among others, of mechanical dry-cleaning in cultural heritage are manual techniques and dry abrasive microblasting. Using different tools, manual procedures are based on the use of energy to break the bonding between soiling and substrate mainly by friction or by cutting actions [7,8].

For the same purpose, microblasting is carried out by particles (in lieu of tools in this case) blasted at the support in a flow of compressed air [9,10] by breaking the bonding between soiling and substrate through impact, cutting or friction mechanisms as well as the manual procedures. Different types of particles have been tested for microblasting on some sensitive surfaces [8,11,12] and also on mock-ups of soiled wood [13], but not on sensitive and fragile wooden heritage objects, in order to compare their effects with other dry-cleaning techniques.

In the reference bibliography on cleaning cultural heritage made of wood, very few references document the usual practices of conservators-restorers for cleaning unpolychromed or uncoated wood. However, the consultation conducted during a workshop with a group of 19 professionals in the conservation-restoration of paintings on wood regarding the methods used to clean unpolychromed wood of cultural heritage has provided a very important firsthand source of information. The authors have been able to confirm the use of cleaning tools and instruments even though written references were rarely found, including different types of brushes and scrapers—bristle, plastic, and metal—metal tools, scouring pads, and also erasers and vulcanized rubber sponges, either in block or powder form [14,15].

Some of these tools and instruments cited by conservator-restorers in the workshop have been used in this study to better determine their cleaning results on wood in poor condition: soft and long-bristle paintbrushes, hard and short-bristle paintbrushes, plastic bristle brushes, metal bristle brushes, vulcanized rubber sponges, and grated erasers have been tested to compare their cleaning results with those obtained by microblasting of powdered lignocellulosic particles.

Traditional dry-cleaning systems used to clean unpolychromed wood have generally given poor results. Some of them cannot reach an acceptable level of cleanliness but are good at respecting the wooden surface. Others are good at cleaning soiling from the wood but cause damage to its surface.

In practice, over years of conservation of wooden supports, every traditional mechanical dry-cleaning started with the aspiration of loose particles of soiling with the aid of a soft brush to sweep it to a vacuum cleaner with adjustable suction power. If after this initial soft vacuuming adhered soiling remains on the surface, then a dry-cleaning technique to remove this adhered soiling can be considered. If the initial vacuuming shows a good cleaning result no other cleaning treatment should be carried out. The results of this second major cleaning step to remove adhered soiling are the object of this study.

After this major cleaning step, the cleaning system residues mixed with the loosened dirt must be removed with a soft brush and a vacuum cleaner to observe the cleaning results and to avoid leaving residues on the surface [16].

The authors reported on tests using microblasting of different lignocellulosic powder particles to clean non-heritage wood samples [13]. In that work, three types of particles from agro-industrial waste were tested: hazelnut and almond shell dust (Aval®), rice

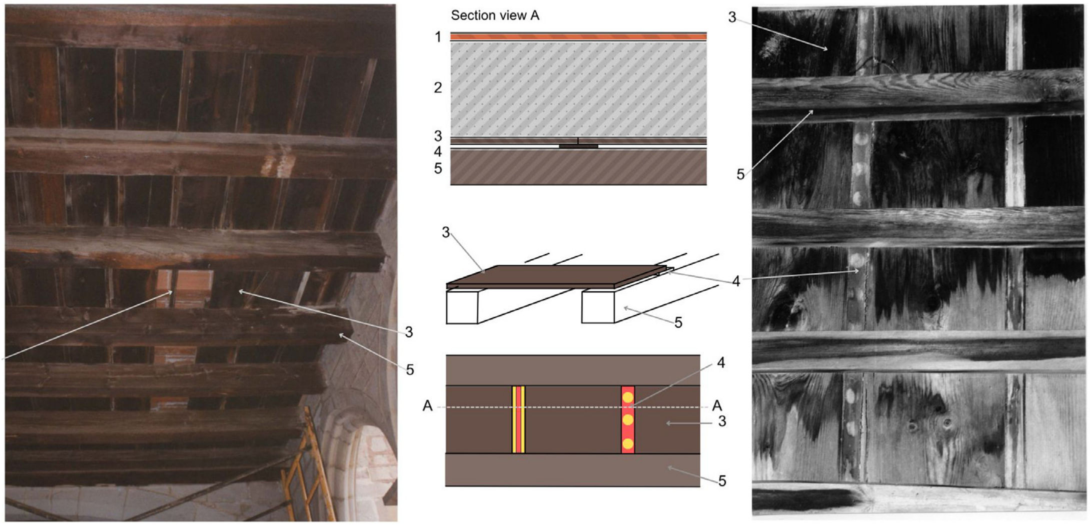

Fig. 1. Photographs of the coffered ceiling of the Royal Monastery of Santa Maria de Pedralbes and diagram of the layout of the elements of the ceiling in different sections. They are not drawn to scale. The elements represented in the cross-section are (1) Ceramic tiles of the top floor; (2) Hydraulic mortar; (3) Unpolychromed wooden boards; (4) Polychrome wooden joint cover; (5) Unpolychromed beams. Images courtesy of the Museum of the Monastery.

husk dust (Oryzite®), and cork dust. The results were compared with those of cellulose fibres (Arbocel® BWW 40). In this study, we tested those that achieved the best results in terms of cleaning wood soiling along with the greatest respect for the treated surface. These turned out to be pure cellulose (Arbocel® BWW 40), almond and hazelnut shell dust (Aval®), and cork dust on a fragment of a ceiling joint cover in poor condition. The use of lignocellulosic material from food industry waste adds value to this process, as it reintroduces natural secondary raw materials into the life cycle without modifying them in any way, turning them back again into a useful material, in line with the United Nations Sustainable Development Goals [33].

Arbocel® has a long tradition of use in various conservation-restoration processes [11,17,18]. However, it is by far the least ecological and sustainable, as its carbon footprint –defined as the quantity of CO_2 generated by its production– is enormous compared to almond and hazelnut shell dust (Aval®) or cork dust. To produce Arbocel®, the necessary water and energy consumption, combined with environmental pollution—caused by the chemicals needed to obtain pure cellulose from wood—make it a very unsustainable material [19]. However, both the process of obtaining almond and hazelnut shell dust (Aval®) and the dust obtained in the process of cutting wine corks generate practically no added ecological footprint to the agro-industrial processes, and the fact of repurposing them for different uses extends their useful life, reincorporating the agro-industrial waste into the value chain of raw materials [20,21].

As indicated in Iglesias–Campos et al. [13], if residues of the particles used for microblasting cleaning remain on the treated wood surface they would pose no risk to the surface, nor to its conservation, as these residues are lignocellulosic and they have a chemical composition similar to wood (cellulose, hemicellulose, and lignin), and are completely biocompatible with the treated object because no different compounds are introduced on it.

Regarding polychromy, micro-blasting is not a suitable cleaning technique a priori. The fragility of the pictorial layers is usually greater than that of the wooden support on which they were applied. Both the pictorial technique and the condition of the polychromy are elements that must be given priority attention when performing microblasting tests. And this would require a separate investigation.

2. Research aim

This work analyses the feasibility of the microblasting technique using powdered lignocellulosic particles for cleaning soiling from unpolychromed wood of a damaged and weakened heritage artwork. The research aims to evaluate the advantages and drawbacks of this method as a mild and sustainable alternative in comparison to the traditional techniques used by conservator-restorers for unpolychromed wood cleaning.

To achieve this objective, results of traditional mechanical cleaning on unpolychromed wood are described and compared qualitatively with those obtained by microblasting with powdered lignocellulosic particles, both applied to the reverse side of a wooden joint cover from a medieval ceiling deteriorated by fungi and woodworm.

3. Artwork

The monastery of Santa Maria de Pedralbes (Barcelona, Spain) was founded in 1326, and its construction continued over the centuries [22]. A large part of the rooms in the different spaces of the monastery feature ceilings that follow the same decorative pattern, consisting of beams on which the wooden boards rest. To prevent the seepage of hydraulic mortar that waterproofs and strengthens the upper floor or the roof, a joint cover decorated with the heraldic symbols of the founders, King Jaume II and Queen Elisenda de Montcada, was incorporated. These joint covers between board longitudinal joints were the only originally polychromed element of the ceilings [Fig. 1].

Throughout the 20th century, some maintenance works, pest disinfestation treatments, and repair interventions carried out at the monastery led to the dismantling of some areas of the ceiling and the removal of the joint covers that were in the worst condition. These fragments of joint covers are currently preserved in the monastery museum. Most have not been cleaned since then and are an example of a wooden cultural asset in a poor condition, which is why their reverse sides were chosen to conduct cleaning tests.

The wooden joint cover fragments are wooden strips from tangential cutting and have a trapezoidal cross-section, with bevelled longitudinal edges of the polychrome face. They have irregular

Fig. 2. Front and back side of two joint covers from the ceiling of the Monastery of Pedralbes with evident signs of biodeterioration. (1) Growth rings showing a tangential cut; (2) Tunnels caused by xylophagous insects, resulting in loss of material and density in the wood; (3) Parallel marks from the saw used to cut the strip with which the joint cover was made; (4) Front side with polychromy remains. Faced with a cleaning treatment, the wood of the back side is now as weak and delicate as paper or cardboard.

lengths as a result of their breakage, due to the nonprofessional method used to remove them from the ceiling. The width of the preserved fragments is fairly regular and ranges from 4 to 4.3 cm, with a thickness of between 0.3 and 0.4 mm.

The surface of the reverse side of the joint cover is rough and irregular. It was not sanded after being cut, nor polychromed, because this part of the object was not supposed to be seen. As a result, tool marks can be easily observed, such as parallel saw marks showing the fibres corresponding to the tangential cut of the growth rings uplifted by the saw cut. [Fig. 2]. To this intrinsically irregular surface, the presence of galleries caused by xylophages and the cubic pattern breakings caused by fungi during the biological degradation process added an extra irregular surface of this reverse side, making cleaning a major challenge.

Soiling adhesion to the wood is related to the surface characteristics such as texture, porosity or elasticity, as well as to the characteristics of the soiling itself [23]. The more irregular the surface the better adhesion of the soiling, because of the increase in the specific surface area where soiling can be settled. Furthermore, wood is a porous structure and a hygroscopic material, characteristics that make wood prone to the fixture of soiling on its surface.

4. Materials and methods

4.1. Wood identification

One of the first steps undertaken was the analysis of the wood from the joint cover used for cleaning tests, to determine the wood genus and its anatomical structure. The analysis was carried out using histological preparation with double staining (methylene blue and safranin) [24,25] and observation under an OLYMPUS® BX51 polarizing light microscope –at 50 ×, 100 × and 200 × – of the three sections (transverse, tangential, and radial) of a sample from one of the joint cover fragments provided for the tests, using both direct transmitted and polarised light. The wood identification was carried out using a key for identifying coniferous woods [26] and the use of specialized bibliography [27].

4.2. Wood surface analysis, dirt characterisation and evaluation of cleaning results

The observation and analysis of the dirt accumulated on the reverse side of the joint covers were conducted using surface microscopy and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS).

The first control of the surface was made using a simple Dino-Lite® digital surface microscope (AM4113-FVW Dino-Lite® microscope with switchable white and ultraviolet (UV) light 395 nm) to examine the surface of the joint cover before and after cleaning treatment using visible, raking and UV light. Images were taken at 65 × with direct light emitting diode (LED) white light and UV (90°) from the microscope and external raking white light (35° and 4 cm distance) from a fibre optical illuminator (ISO 9001) regulated at position 1. Images were processed with 2.0 Dino-Capture® software.

To evaluate the cleaning effects on the reverse side of the joint cover, the surface was analysed by SEM-EDS before and after cleaning procedure. We used a FEI ESEM QUANTA 200, a thermionic emission microscope (tungsten filament) with a resolution of 2 µm attached to the UltraDry EDS detector (Thermo Fisher Scientific), which has a diameter of 30 mm.

Each sample was placed on a conductive carbon adhesive tape fixed to a SEM aluminium stub and placed unprepared into the SEM chamber. Secondary electron (SE) images, backscattered electron (BSE) images and elemental analyses were obtained under a low vacuum mode with an accelerating voltage of 20 kV. The images were taken under magnifications 65 ×, 500 × and 1000 × . When possible, several analyses were performed on items displaying similar features. The EDS analyses were carried out at the same working distance (around 10 mm) and with the same acquisition time (50 s) for each EDS spectrum. The software used for spectrum acquisition and processing was Pathfinder Alpine (Thermo Fisher Scientific). To avoid any misunderstanding with the quantifications, the expression “major”, “minor” and “trace” elements rather than actual numbers was used.

Table 1
Main properties of the tested lignocellulosic particles.

Material	Natural cellulose fibres (Arbocel®)		Powdered almond and hazelnut husks (Aval®)		Cork sawdust	
Composition	~98.0 %	cellulose	35.86 %	lignin	50 %	suberin
	~1.50 %	ash	48.00 %	cellulose	20–25 %	lignin
			2.76 %	fat	20 %	cellulose and hemicellulose
			2.22 %	protein	~1.5 %	pectins
			1.08 %	ash	~14–18 %	extractives
					~1–2 %	ash
Morphology	Cylindrical (elongated)		Angular (polyhedral)		Rounded	
Particle size (μm)	≤200		≤200		≤125	

Table 2
Microblasting equipment and parameters used in the tests.

Equipment	Microblasting CTS 5/B Silenced compressor 1.5CV – Mod. AIRBAG (CTS) Dehumidifier filter CTS 8 Sandblasting cabinet (CTS) with external vacuum cleaner
Nozzle	Ø 0.7mm Straight tungsten carbide nozzle - CTS Fixed on a lab clamp (maintaining distance and angle)
Pressure	20 kPa (2.9 psi)
Distance	10 cm
Angle	90°
Time	10 s

4.3. Materials selected for microblasting cleaning

Three different particles (Aval®, Cork and Arbocel® BWW 40) were selected from the results of initial studies [13].

Aval® and Cork are natural raw powdered particles coming from residues or sub-products of the food industry. Aval® is obtained from the crushing of almond (*Prunus dulcis*) and hazelnut (*Corylus avellana* L.) shells. Cork sawdust is the bark of *Quercus suber* L., the cork oak tree, resulting from the sawing of cork planks.

Arbocel® processed pure cellulose fibres, was selected as a soft material that has been previously tested on paper and fabric supports [12,28,29] to compare the results with those of vegetable particles. In these tests, Arbocel® BWW 40 was chosen because its fibres have a size similar to the vegetable particles.

The lignocellulosic particles were supplied by manufacturers in different sizes. For the experimental study, particles ≤ 200 μm were selected to avoid blockages in the small nozzle diameter used. To prevent clogging, the largest material (Cork sawdust) was further sieved using a standardized 0.125 mm sieve (ISO 3310/1).

The main properties of these particles related to their use for microblasting are indicated in Table 1.

4.4. Microblasting of lignocellulosic materials

The microblasting technique is based on the kinetic energy formula [$KE = \frac{1}{2}\ m\ \times\ v^2$], where m is mass (abrasive); and v, velocity (pressure) [10]. This indicates that it is directly proportional to the mass of the particle and to the square of its velocity. Nozzle diameter, pressure, distance, angle, time, flow of particles, and specific abrasive properties (composition, size, specific weight, density, morphology, hardness, friability or toughness, etc.) are important parameters to be considered.

Similar to preliminary tests carried out on wooden mock-ups, the equipment used, and parameters are listed in Table 2.

During cleaning, the joint cover was moved horizontally in the wood grain direction simulating the restorer's hand movement in an actual cleaning process because a 0.7 mm diameter nozzle from a 10 cm distance to the surface does not clean the whole test area.

Test areas were covered with a cardboard on which a reserve of 7 cm^2 (3.5 cm × 2 cm) was cut to standardise the microblasting area. To control as far as possible the homogeneity of the treatment, testing areas were covered with a cardboard until a constant flow of particles was achieved. The same protection was used to prevent the abrasive to impact the surface at the end of the treatment. During tests, an assistant was timing the treatment and protecting and uncovering the surface.

After cleaning treatments, when loose residues from the cleaning materials might remain on the wood surface a thin, soft nylon paintbrush and a vacuum cleaner (Museum Muntz® 555-MU-E HEPA), equipped with a flat section nozzle, were used to gently sweep the surface, reproducing a common procedure after a dry-cleaning process [16].

4.5. Traditional mechanical techniques

In this study, different mechanical cleaning techniques were used to assess their effectiveness and impact on the treated surface. The traditional techniques tested included: a long nylon-bristle paintbrush (i), a round short-bristle paintbrush (ii), an Akapad® soft sponge (iii), powdered eraser (Milan® 430) were applied and subsequently removed with a soft long-bristle paintbrush (iv), a nylon-bristle brush (v) and a brass-bristle brush (vi) which were chosen to compare its results with lignocellulosic microblasting technique. The protocol in all the tests included a mild initial vacuuming to remove loose particles, followed by the application of the tested cleaning system in the wood grain direction, making repeated cycles for a total time of 10 s. Finally, a second mild vacuuming was carried out to remove any loose residues generated during cleaning, reproducing a common procedure after treatment [16].

To compare both traditional mechanical techniques and microblasting, different parameters were selected from referenced literature on cleaning evaluation [8,16,30,31,32], focusing on two main aspects: surface cleanliness and wood surface integrity after cleaning. Additionally, the presence of residues from the cleaning materials was also monitored, considering qualitative aspects. Table 3 outlines the criteria used to rate each of the evaluation parameters.

5. Results and discussion

5.1. Wood identification results

The biodeterioration of the wooden joint covers rendered the identification process by vegetal histological techniques difficult. According to the patterns observed in the cross-section image [Fig 3.A], the wood of the joint covers is coniferous, with well-differentiated growth rings where no resin channels can be

Table 3
Parameters for evaluating the cleaning techniques (both mechanical manual and microblasting of powdered lignocellulosic particles) tested in this work.

Parameter	Rating of 1	Rating of 2	Rating of 3	Rating of 4
Soiling removal efficiency	No effect	Minimal removal	Moderate removal	Good removal
Soiling removal evenness	Uneven removal	Inconsistent removal	Moderately removal	Complete removal
Cleaning system residues	Surface covered by particles	Surface partially covered by particle residue	Minor particle residue noticeable	No noticeable residue
Changes on wood surface	Complete surface changes with wood loses	Moderate surface changes with wood loses	Minimal changes on wood surface with breakage or movement of fibres	No noticeable changes that modify the wood surface
Cleaning process control	No control of cleaning process	Poor control of cleaning process	Moderate control of cleaning process	Full control of cleaning process

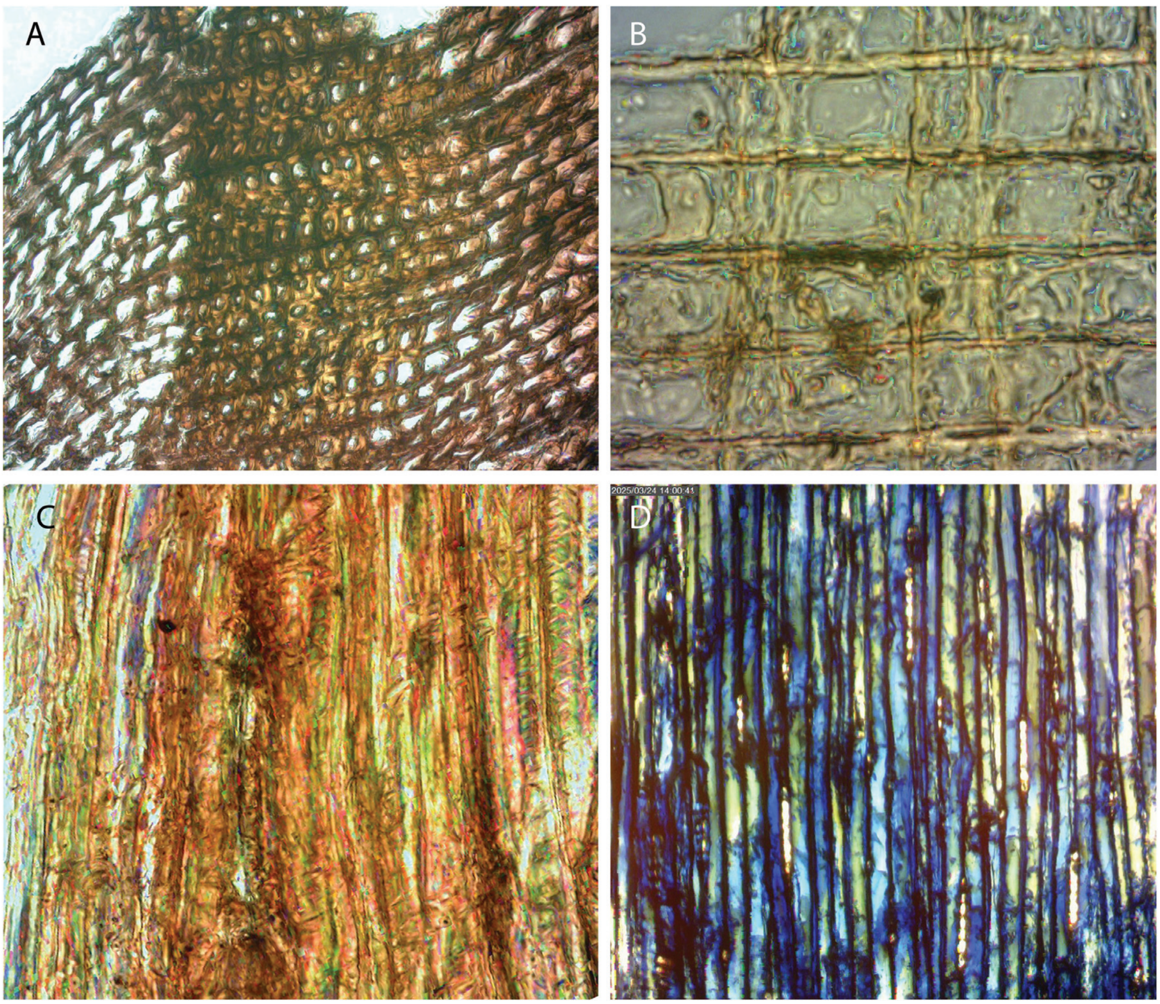

Fig. 3. Optical microscope images (transmitted and polarised light) of the transversal, radial and tangential sections of a 5 mm x 2 mm x 2 mm sample of wood from one of the joint covers from the coffered ceiling. Sections obtained manually, with the aid of a razor blade, prepared with double staining with methylene blue and safranin: (A) transversal section (100 ×); (B) radial section (200 ×); (C) tangential section (200 ×); (D) tangential section (100 ×).

observed. The cross-section of the tracheids is square, although in the image the tracheids appear deformed due to the poor condition of the wood in the sample used to obtain the section. The transition from spring to summer wood is abrupt as observed in the right half of the image. No longitudinal parenchyma cells are identified in the cross section of the samples obtained.

The radial section image [Fig. 3.B] shows procumbent parenchyma cells alternating with radial tracheids intersecting with longitudinal tracheids and parenchyma cells. In the cross fields there are 1 to 2 window-like pits.

The image obtained at 100 × of the tangential section of the sample shows uniseriate rays, between 1 and 10 elements high, and areolate pits (scarce) [Fig. 3.D]. The image obtained at 200 × clearly shows the helical thickening of the tracheids [Fig. 3.C].

According to the observed elements and bibliographic references [26,27], the wood of the joint covers has been identified as belonging to the genus *Pinus* and is probably *Pinus Mugo*.

5.2. Soiling composition

Results regarding soiling's textural and compositional features are displayed in Table A.1 and Figs. A.1 to A.6. The soiling adhered on the surface of the samples is mainly composed of aluminosilicates (Si, Al; in the form of clay minerals, feldspars and, to a lesser extent, micas), silicates (Si; probably quartz), a calcium-rich

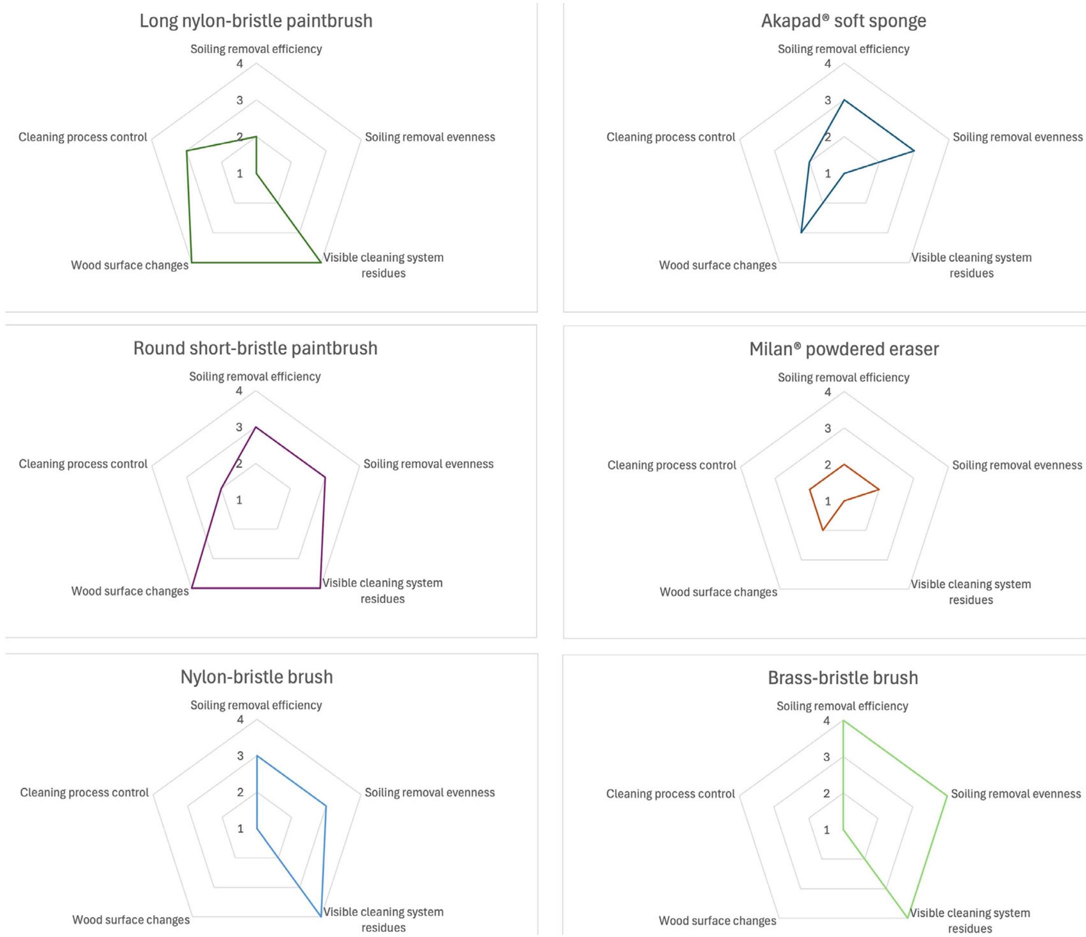

Fig 4. Evaluation of mechanical traditional dry-cleaning mechanical techniques tested in this work. (For the list of evaluation criteria and an explanation of the rating scores, refer to the "Materials and Methods" section, Table 3).

undetermined compound (Ca; probably lime), and metallic particles (Fe; oxi-hydroxides). These compounds probably originate from the formwork itself, in which one may find a layer of mortar made with an admixture of hydraulic lime and clay (Fig. 1).

5.3. Traditional mechanical cleaning results

The five key parameters mentioned in previous studies [8,16,30,31,32] were used to evaluate mechanical cleaning techniques.

Results for each cleaning system are described below and summarized in Fig. 4 (star diagrams evaluation of traditional mechanical cleaning techniques) and Fig. 5 (comparison images of cleaning results with the different traditional tools used).

The long nylon-bristle paintbrush showed a minimal dirt removal, only incoherent and loose adhered dirt was cleaned. No visible cleaning effect was observed to the naked eye, but a partial soiling removal was evident under magnification. Cleaning was uneven with considerable dirt particles remaining on the surface. No visible changes on wood surface were detected. The procedure enabled a limited cleaning control.

The short bristle round paintbrush enabled moderate uniform dirt removal. Digital optical microscopy confirmed a significant reduction of soiling. The treatment did not cause any noticeable change to the wood surface and the cleaning process was poorly controlled.

The Akapad® soft sponge had similar results to the short bristle round paintbrush, with moderate and fairly uniform soiling removal. Despite vacuuming, the surface was partially covered by visible sponge particle residues between the wood fibres. Minimal surface changes were observed on wood and the cleaning process was difficult to control.

With the Milan® 430 powdered eraser, a partial removal of dirt was achieved. After treatment, the surface was covered by visible particles because eraser residues were accumulated between the fibres. In addition, it caused moderate change on wood surface due to material loss by displacing a significant number of fibres. Control of the cleaning process was poor.

The nylon-bristle brush removed dirt unevenly leaving some embedded dirt particles in the treated surface. It also caused significant damage to the wood surface by breakage, displacement and loss of fibres. No visible residues remained after cleaning, but control process was very poor due to its aggressive action.

Both, Milan® 430 eraser and nylon bristle brush have caused noticeable fibre displacement, visible under magnification, compromising surface cohesion.

Finally, the brass-bristle brush removed soiling but damaging the wood structure in the process by breaking fibres and leaving visible galleries made by xylophagous insects which were previously not exposed. The damage caused to this sensitive surface is obvious. The procedure was very aggressive and uncontrollable with irreversible damage to the wood surface.

5.4. Microblasting cleaning results

The same key parameters were also used to evaluate microblasting cleaning tests. The results obtained for each cleaning system are described below and illustrated in the star diagrams

Fig. 5. Comparison of cleaning results with different traditional dry-cleaning tools: long nylon bristle paintbrush and its cleaning results in Area 1; short bristle round paintbrush and its cleaning results in Area 2; Akapad® soft sponge and its cleaning results in Area 3; Milan® 430 powdered eraser and its cleaning results in Area 4; nylon-bristle brush and its cleaning results in Area 5; brass bristle brush and its cleaning results in Area 6 (Dino-Lite® images before and after cleaning at 65 × show wood fibres displayed horizontally for each area).

[Fig. 6] and in the comparative images of surfaces before and after cleaning [Fig. 7].

Overall, the result was significantly better compared to traditional dry-cleaning systems. Microblasting offers full control over the process by allowing precise adjustment of pressure parameter. In addition, distance and angle can be accurately set to minimize impact on the surface [Fig. 7]. It should be pointed out that with both microblasting and traditional mechanical methods, training and experience is essential for cleaning.

Regarding the efficiency of soiling removal with all lignocellulosic particles, the observation through Dino-Lite® at 65 × after microblasting showed a better dirt removal compared to traditional manual methods, resulting in homogeneous surfaces with no visible changes. These results were confirmed by SEM [Figures A.1 to A.3].

For soiling removal evenness, an apparent uniform removal without areas of residual dirt was observed. However, observation through SEM at 500 × revealed differences among the results achieved with each lignocellulosic material. Concerning Arbocel® BWW 40, a moderately clean surface is observed, where the less embedded particles have been removed from the surface after a 10 s cleaning session, but the dirt in the cavities of the substrate remains adhered. The uniformity of the cleaning is uneven depending on the areas observed. In the case of Aval®, the level of cleanliness achieved is superior to that of Arbocel®. Less dirt is observed on the wood surface after a 10 s cleaning session, and a uniform removal of dirt particles is achieved. Finally, after a 10 s cleaning, the cork sawdust fulfilled the soiling removal criteria better than other particles tested. Most of the dirt is removed from the surface, leaving only smaller particles embedded in some cavities.

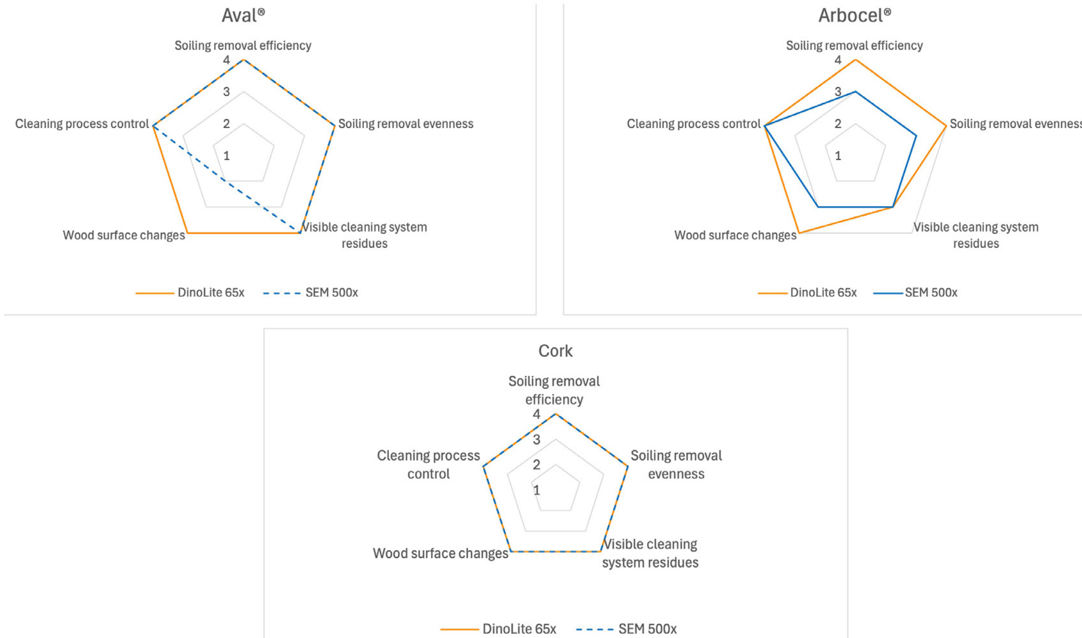

Fig. 6. Evaluation of the microblasting of powdered lignocellulosic particles cleaning tests. The orange colour highlights the cleaning results observed with DinoLite at 65 ×, while the blue colour indicates the results observed with SEM at 500 × . (For the list of evaluation criteria and an explanation of the rating scores, refer to the "Materials and Methods" section, Table 3).

Concerning the visible residues after cleaning, it must be pointed out that generally no visible residues were observed with Dino-Lite® at 65 × after vacuuming. However, a very small amount of the white Arbocel® residues were visibly locatable within the wood fibers under UV light, but not visible to the naked eye. These results were confirmed by SEM.

Looking at changes on wood surface after a 10 s cleaning session no noticeable modifications were observed with Dino-Lite®. Under SEM, some differences can be observed in the effect caused by the different particles. In the case of Arbocel®, the surface has been preserved during cleaning, although some wood fibres have been displaced. The larger cracks have been filled with the blasted powder. Regarding Aval®, the wood surface is slightly abraded after the cleaning process. The edges of the fibres and the rims of the holes are eroded. Some loosely bound wood fragments disappear from the surface. As for the cork dust, the wood surface remains well-preserved. No changes in the arrangement of the fibre or eroded areas are observed.

The comparison of the pre-cleaning and post-cleaning stages [Fig. A.4] also illustrates the changes in elemental composition of surfaces during the cleaning process. EDS microanalysis reveals that Arbocel® BWW 40 can remove most of the soiling particles (such as Si, Al, K, Fe, Ca) without damaging the wood surface (C).

Aval® microblasting shows a very clear decrease of aluminosilicates (Si, Al, K, Mg) and Fe-rich particles. Also, after cleaning, the carbon (C) peaks corresponding to wood clearly appear in the spectra [Fig. A.5].

Changes in the surface composition after cleaning with cork powder are significant. Aluminosilicates and iron-rich particles are removed, as in the case of Aval®, and the carbon peak (wood) becomes very clear after cleaning. In specific areas with embedded dirt, the composition of the dirt does not change. No cork residues are observed, even in these areas.

Finally, regarding the cleaning process, it is worth highlighting that maintaining microblasting technical parameters in all situations, an accurate and reliable cleaning was achieved in all tests [Fig. A.6]

6. Conclusions

Results indicate that when the microblasting technique is applied properly, an appropriate cleaning level can be achieved without compromising the fragile treated surface with negligible presence of residues after vacuuming. Control of the overall cleaning process through the appropriate selection of abrasives and treatment parameters is very important to prevent unwanted changes to the surface. Therefore, this approach emerges as a promising and environmentally friendly technique, respectful to the integrity of the wooden artworks.

From the analysis of the tests carried out, cork achieves a higher cleaning effect without causing changes in the fibres of this joint cover. It is the system that scores best in all the items evaluated. Aval® obtains also good results in soling removal efficiency, soiling removal evenness, visible cleaning system residues and cleaning process control. However, it does not fulfil most of the determined key parameters as visualised by star diagrams. related to changes on the wood surface. Using the same treatment time as for the other lignocellulosic particles, it is more abrasive. As Aval® is more abrasive than cork and Arbocel® BWW 40, it takes less time to reach the dirt removal target and once the dirt is removed, the impact on the wood causes a slight abrasion of the surface.

In the same treatment time as cork and Aval®, Arbocel® BWW 40 obtains the highest score in cleaning process control but does not perform as well in soling removal efficiency, soiling removal evenness, visible cleaning system residues and wood surface changes. Where it scores poorest –both for the Dino-Lite and SEM observation– is on visible cleaning system residues. The residues are white and easily detectable also under UV light, because they emit a clear fluorescence. In the case of Aval and cork dust no residues are observed after application.

Results also point out that it is necessary to conduct tests on discrete areas with the different lignocellulosic particles, to verify the effect on each wooden object to be treated, before selecting the specific particle and the microblasting technical parameters to be used. Control of the overall cleaning process through the ap-

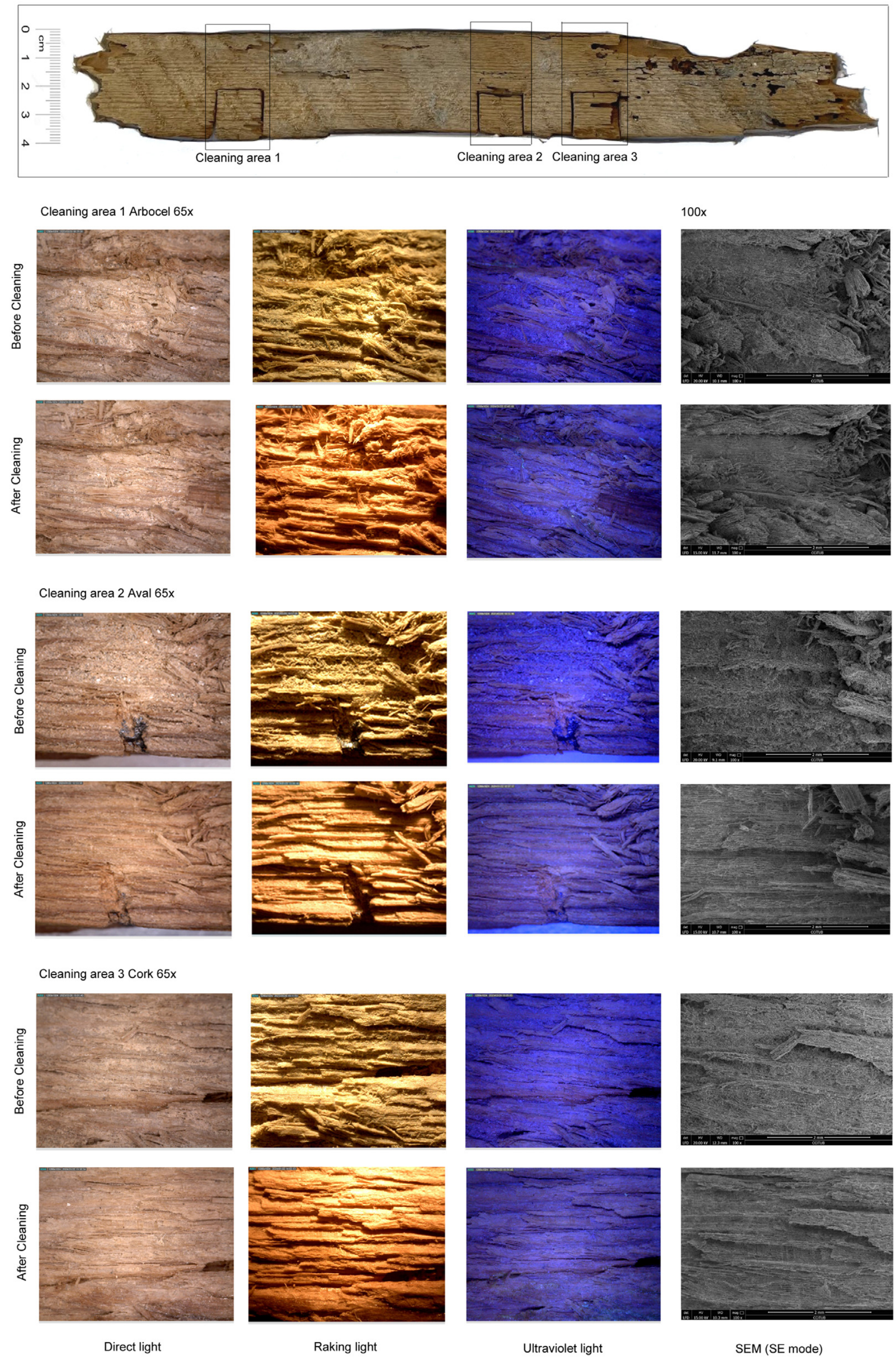

Fig 7. At the top of the image, the joint cover fragment with the three cleaning tests performed using lignocellulosic particle microblasting. From left to right: test conducted with Arbocel® BWW 40 in area 1; with Aval® in area 2; with cork dust in area 3. Below the image of the joint cover, a zone from each area viewed with Dino-Lite® (65 ×) under direct light, raking light, UV light before and after cleaning with each type of dust. In the last column, an image of the same zone viewed with SEM BSED (65 ×) before and after cleaning.

propriate selection of particles and treatment parameters is very important to prevent unwanted changes to the surface.

In addition, the results obtained both in this study – performed on a heritage artwork – and in the previous one – conducted on mock-ups – indicate a trend in how different microblasted lignocellulosic particles have an influence on soiling removal and the potential effects on the surface.

However, these results have not been tested on hardwoods. Therefore, future tests should verify their applicability to woods of varying hardness and different anatomic structures.

Another important point is that the residues of lignocellulosic particles remaining on the surface after the final soft vacuuming, are very scarce. These very few residues, if any, are chemically compatible with the treated wood because they are predominantly composed of cellulose, hemicellulose, lignin and other vegetable compounds, which are some of the main wood constituents.

Finally, it should be noted that, except for pure cellulose, the particles used are residues from various processes in the food industry and their use aligns with the Sustainable Development Goals (SDGs).

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2025.12.012.

References

[1] F. Descamps (Ed.), Methodology for the Conservation of Polychromed Wooden Altarpieces: An International Conference Organized by the Getty Conservation Institute and the Instituto Andaluz del Patrimonio Histórico, Seville, May 2002, Junta de Andalucía & J. Paul Getty Trust, 2006 http://hdl.handle.net/10020/gci_pubs/retablos_2002_english (Accessed 13 Jul 2024).

[2] J. Wadum, Historical overview of panel-making techniques in the Northern Countries, in: K. Dardes, A. Rothes (Eds.), The Structural Conservation of Pannel Paintings: Proceedings of Symposium at the J. P. Getty Museum, 1998, pp. 149–177. Vol. 2.

[3] A. Seim, J. Edvardsson, A. Daly, et al., Timber trade in 17th-century Europe: different wood sources for artworks of Flemish painters, Sci. Rep. 14 (2024) 18216, doi:10.1038/s41598-024-68641-y.

[4] G. Caneva, S. Ceschin, Ecologia del biodeterioramento, in: G. Caneva, M.P. Nugari, O. Salvadori (Eds.), La Biologia Vegetale Per i Beni Culturali. Biodeterioramento e Conservazione, Nardini Editore, Firenze, 2005, pp. 35–41. Vol. 1.

[5] D. Pinna, O. Salvadori, Meccanismi generali dei processi de biodeterioramento, in: G. Caneva, M.P. Nugari, O. Salvadori (Eds.), La Biologia Vegetale Per i Beni Culturali. Biodeterioramento e Conservazione, Nardini Editore, Firenze, 2005, pp. 25–27. Vol. 1.

[6] O. Pasquariello, O. Maggi, M.A. Persiani, Processi generali di biodeterioramento dei materiali di origine vegetale, in: G. Caneva, M.P. Nugari, O. Salvadori (Eds.), La Biologia Vegetale Per i Beni Culturali. Biodeterioramento e Conservazione, Nardini Editore, Firenze, 2005, pp. 99–100. Vol. 1.

[7] B. Ormsby, A. Bartoletti, K.J. van den Berg, C. Stavroudis, Cleaning and conservation: recent successes and challenges, Herit. Sci. 12 (2024) 10, doi:10.1186/s40494-023-01113-0.

[8] L.P. Stoveland, T. Frøysaker, M. Stols-Witlox, et al., Evaluation of novel cleaning systems on mock-ups of unvarnished oil paint and chalk-glue ground within the Munch Aula Paintings Project, Herit. Sci. 9 (2021) 144, doi:10.1186/s40494-021-00599-w.

[9] B.M. Gibson, The use of the airbrasive process for cleaning ethnological materials, Stud. Conserv. 14 (4) (1969) 155–164, doi:10.1179/sic.1969.017.

[10] M.A. Iglesias-Campos, S. Garcia-Fortes, J.L. Prada-Perez, Influence of projection angle in sandblasting cleaning on detrictic stone materials, Mater Constr. 64 (314) (2014) e021, doi:10.3989/mc.2014.02113.

[11] I. Alexopoulou, S. Zervos, Paper conservation methods: an international survey, J. Cult. Herit. (21) (2016) 922–930, doi:10.1016/j.culher.2016.04.001.

[12] M.Á. Iglesias-Campos, C. Ruiz-Recasens, E. Díaz-Gonzalez, First experiments for the use of microblasting technique with powdered cellulose as a new tool for dry-cleaning artworks on paper, J. Cult. Herit. 15 (4) (2014) 365–372, doi:10.1016/j.culher.2013.09.001.

[13] M.A. Iglesias–Campos, et al., Microblasting with vegetable and cellulosic media for heritage wood cleaning: effects on surface morphology, Herit. Sci. 12 (2024) 233, doi:10.1186/s40494-024-01347-6.

[14] Care and Cleaning of Unfinished Wood. CCI Notes 7/1, Canadian Conservation Institute, 2017 https://www.canada.ca/en/conservation-institute/services/conservation-preservation-publications/canadian-conservation-institute-notes/care-unfinished-wood.html (Accessed 4 September 2024).

[15] S. Hamed, M.F. Ali, N. Elhadidi, Assessment of commonly used cleaning methods on the anatomical structure of archaeological wood, Int. J. Conserv. Sci. 4 (2) (2013) 153–160 https://ijcs.ro/public/IJCS-13-16-Hamed.pdf. (Accessed 13 July 2024).

[16] M. Daudin-Schotte, et al., Dry cleaning approaches for unvarnished paint surfaces, in: M. Mecklenburgh, E. Charola, R.J. Koestler (Eds.), New Insights into the Cleaning of Paintings: Proceedings from the Cleaning 2010 International Conference, Universidad Politécnica de Valencia and Museum Conservation Institute, Smithsonian Institution Scholarly Press, Washington DC, 2013 Smithsonian Contributions to Museum Conservation, doi:10.5479/si.19492359.3.1.

[17] K. Fulcher, An investigation of the use of cellulose-based materials to gap-fill wooden objects, Stud. Conserv. 62 (4) (2016) 210–222, doi:10.1080/00393630.2015.1109294.

[18] A. Sáenz-Martínez, M. San Andrés, M. Alvarez de Buergo, I. Blasco, R. Fort, Removing Calcium Carbonate deposits from archaeological ceramics. Traditional methods under review, Mediterr. Archaeol. Archaeom. 19 (3) (2019) 107–117, doi:10.5281/zenodo.3583061.

[19] E. Sjöström, U. Westermark, Chemical composition of wood and pulps: basic constituents and their distribution, in: Analytical Methods in Wood chemistry, pulping, and Papermaking, Springer Berlin Heidelberg, Berlin, Heidelberg, 1999, pp. 1–19.

[20] I. Prado-Acebo, et al., Integral multi-valorization of agro-industrial wastes: a review, Waste Manag. 183 (2024) 42–52, doi:10.1016/j.wasman.2024.05.001.

[21] E. Lizundia, F. Luzi, D. Puglia, Organic waste valorisation towards circular and sustainable biocomposites, Green Chem. 24 (2022) 5429–5459, doi:10.1039/D2GC01668K.

[22] Reial Monestir de Pedralbes (n.d). https://www.monestirpedralbes.barcelona/en/monastery/history/14th_century_foundation_monastery (Accessed 26 January 2025)

[23] A. Phenix, A. Burnstock, The deposition of dirt: a review of the literature, with scanning electron microscope studies of dirt on selected paintings, in: V. Todd (Ed.), Dirt and Pictures Separated, UKIC, London, 1990, pp. 11–18.

[24] E. Srebotnik, K. Messner, A simple method that uses differential staining and light microscopy to assess the selectivity of wood delignification by white rot Fungi, Appl. Environ. Microbiol. 60 (4) (1994) 1383–1386 http://doi.org/10.1128/aem.60.4.1383-1386.1994.

[25] W. Schoch, I. Heller, F.H. Schweingruber, F. Kienast, Wood Anatomy of Central European Species, 2004 https://www.wsl.ch/land/products/dendro/preparation.html (Accessed 15 July 2025).

[26] L. García Esteban, A. Guindeo Casasús, P. De Palacios, Clave de identificación de maderas de coníferas a nivel de especie. Región Europea y Norteamericana, Invest. Agr. 9 (I) (2000).

[27] L. García Esteban, et al., Anatomy and Identification of Conifers Wood as a Species, Fundación Condes Del Valle de Salazar, Ediciones Mundiprensa, Madrid, 2002.

[28] M.Á. Iglesias-Campos, C. Ruiz-Recasens, Surface cleaning of intaglio prints with microblasting powdered cellulose and erasing: treatment effects on inks and support texture, J. Cult. Herit. 16 (3) (2015) 329–337, doi:10.1016/j.culher.2014.08.001.

[29] I. Bautista-Morenilla, C. Ruiz-Recasens, M.Á. Iglesias-Campos, M. Oriola-Folch, Powdered cellulose microblasting: a useful technique for dry-cleaning the reverse side of canvas paintings, Herit. Sci. 10 (2022) 170, doi:10.1186/s40494-022-00796-1.

[30] T. Frøysaker, M. Liu, C. Miliani, Non-invasive assessments of cleaning tests on an unvarnished oil painting on canvas by Edvard Munch, in: M. Mecklenburgh, E. Charola, R.J. Koestler (Eds.), New Insights into the Cleaning of Paintings: Proceedings from the Cleaning 2010 International Conference, Universidad Politécnica de Valencia and Museum Conservation Institute, Smithsonian Institution Scholarly Press, Washington DC, 2010 Smithsonian Contributions to Museum Conservation, doi:10.5479/si.19492359.3.1.

[31] B. Ormsby, J. Lee, I. Bonaduce, A. Lluveras-Tenorio, Evaluating cleaning systems for use on water sensitive modern oil paints: a comparative study, in: K.J. Van den Berg, I. Bonaduce, A. Burnstock, B. Ormsby, M. Scharff, L. Carlyle, G. Heydenreich, K. Keune (Eds.), Conservation of Modern Oil Paintings, Springer, Cham, 2019, pp. 11–35, doi:10.1007/978-3-030-19254-9_2.

[32] A. Bartoletti, R. Barker, D. Chelazzi, N. Bonelli, P. Baglioni, J. Lee, L.V. Angelova, O. Ormsby, Reviving WHAAM! a comparative evaluation of cleaning systems for the conservation treatment of Roy Lichtenstein's iconic painting, Herit. Sci. 8 (1) (2020) 9, doi:10.1186/s40494-020-0350-2.

[33] United NationsTransforming Our World: The 2030 Agenda for Sustainable Development (A/RES/70/1), United Nations, 2015 https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.