Highlights

- Biodeterioration of synthetic polymers in conservation is a concern
- Synthetic polymer-based composites are susceptible to microbial attack
- Selected microorganisms are used to remove undesired synthetic polymers
- Current research gaps and priorities are defined

Interactions of microorganisms and synthetic polymers in cultural heritage conservation

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Abstract Since the 1960s, synthetic polymers (at the time assumed to be resistant to microbial colonization) have been employed to mitigate the ongoing deterioration of cultural heritage. Since then, the use of synthetic materials in heritage conservation attracted much interest. This paper reviews the last two decades of advances in the relationship microorganisms - synthetic polymers in the cultural heritage conservation field. Three topics are considered: (1) biodeterioration of traditional synthetic polymers, (2) biosusceptibility of novel composites based on synthetic polymers, and (3) biocleaning to remove undesired synthetic polymers. It is know that, if the undesired polymer chemical structures are not fully known, they are particularly difficult to remove. Therefore, the future employment of synthetic polymers definitely requires a more critical holistic conservation assessment.

Keywords: biosusceptibility; biodeterioration; biocleaning; acrylics; conservation; microorganisms.

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Contents

1. Introduction

The synthesis of fully synthetic polymers dates back to the 19th century. Early synthetic polymers were polystyrene, polyvinyl chloride, polyisobutylene, polyisoprene and polyaniline (Rasmussen, 2018). After the Second World War, new classes of synthetic resins were introduced, and later in the 1950s and 1960s, as a result of economic growth, polymeric materials became commonly used materials. During the same period, in the sixties, it became popular to employ synthetic polymers to slow down the ongoing deterioration of cultural heritage assets, since it was assumed that they were more resistant than natural materials to microbial colonization. Over the next forty years, according to Doehne and Price (2010), epoxy resins, acrylic polymers, organic silicones and fluoropolymers were the compounds most commonly used for stone conservation. Some acrylics, polyvinyl acetates and alkyds were likewise employed to produce and treat other artworks such as paintings (Cappitelli and Sorlini, 2008). Though the application of synthetic polymers has become a routine practice in consolidation and protection of cultural heritage buildings and objects, their resistance to microbial colonization is questionable from past experience (Gu, 2003).

Many phenomena, processes and/or activities by microorganisms in the synthetic polymers are embraced by the terms biodeterioration, biodegradation and biosusceptibility or bioreceptivity. The most accepted definition of biodeterioration is that offered by Hueck in 1965: ‘any undesirable change in the properties of a material caused by the vital activities of organisms’. A term very close to it, also including positive connotations, is biodegradation (including biocleaning approaches) of which there are several definitions. While no formal definition has been consolidated, the most widely used in the building stone decay and conservation area is that of Allsopp et al. (2004): 'the harnessing, by man, of the decay abilities of organisms to render a waste material more useful or acceptable'. Eggins and Oxley (2001), in a work originally written in 1980, discussed these two terms and showed that both are identical in principle, and their distinction is only made on the basis of human needs. Biodeterioration decreases the value of a material of relatively high value, while biodegradation occurs in materials of little or no value, e.g. for the elimination of waste (Kurowski et al., 2017). In connection with this, the term biodeterioration is closely related to inorganic building materials, mainly stone and masonry from heritage, while biodegradation is often associated with plastic and other synthetic polymeric materials. The terms biosusceptibility or bioreceptivity (the latter defined by Guillitte in 1995 as ‘the ability of a material to be colonised by living organisms’) and biodeterioration are confused in some cases. In addition to the always negative connotations of the biodeterioration concept, the target objectives are the effects of colonisation on the material. In contrast, in the case of bioreceptivity, the focus is on the effects of the material on colonisation.

The presence of microorganisms on synthetic polymers may result in biofouling, the degradation of the polymer and additives/residual monomers and penetration of biological structures or of metabolites like pigments into the synthetic matrix (Flemming, 2010). Indeed, some lipophilic pigments are capable of diffusing into the polymer matrix, leading to ineffective cleaning of the polymer surface (Flemming, 2010). For some of these synthetic polymers, microorganisms and enzymes involved in their degradation have been described (Kurowski et al., 2017; Sabev et al., 2006; Purohit et al., 2020). Gaytán et al. (2021) suggested that acrylics undergo microbial degradation in two steps: the first phase is an enzymatic elimination of side groups and the second step is the cleavage of the C-C backbone. Biochemical processes, mechanisms and initial pioneering species involved in biodeterioration of other synthetic polymers are reported in Mohanan et al. (2020). Several techniques are now available that can detect the presence of microbial growth on polymeric substrates, for example, infrared spectroscopy (Cappitelli et al., 2005) and laser-induced fluorescence scanning (Spizzichino et al., 2015).

This paper presents a concise review on microorganisms - synthetic polymers interactions in cultural heritage conservation related to the last two decades. The three issues examined include: (1) biodeterioration of traditional synthetic polymers, (2) biosusceptibility of composites based on synthetic polymers, and (3) biocleaning to remove undesired synthetic polymers.

2. Synthetic polymers as a habitat for biological colonization

2.1 A growing concern

Despite the fact that biocides are typical additives in artists' acrylic emulsion paints (Learner, 2007), according to the Smithsonian Museum Conservation Institute, fungal development on acrylic paintings is a rising concern among artists and collectors (https://www.si.edu/mci/english/learn_more/taking_care/acrylic_paintings.html#:~:text=Mold%20growth%20has%20been%20noted,when%20humidity%20and%20te mperature%20rise). The American institute stated that no ideal conservation treatment exists and intervention always causes some degree of damage to the original paint.

This is not surprising as, in some instances, synthetic polymers in paints in cans have been found to be already contaminated by microorganisms, especially fungi, mainly *Rhizopus* and *Aspergillus* spp., before application (Okunye et al., 2013). In particular, water-borne coating paints are potentially prone to in-can attacks as a consequence of the use of contaminated recycled water, leading for example to loss of viscosity, pH changes, sedimentation and separation into phases, discoloration, and potential health hazards (Okunye et al., 2013). Similarly, in the interior of spray paint cans in black, red and white colours, *Pantoea* sp., *Bacillus megaterium* and *Pseudomonas mendocina* were found, all of them with potential biocleaning capacity against spray alkyd and polyester resins paint graffiti (Sanmartín et al., 2015).

Primal AC33 and Plexisol P550 40TB 1997 (both purchased in 1997), Primal AC33 (purchased at the beginning of the 1990s), and Paraloid B72 (purchased in 1966) kept in can for decades were tested according to the American Society for Testing and Materials "Standard Practice for Determining Resistance of Synthetic Polymeric Materials to Fungi" (ASTM G21-96(2002), growth rate 0-4, 0=no growth; 4=massive growth) (Cappitelli et al., 2008). In contrast to the results obtained with the same synthetic resins recently acquired, the polymers naturally aged in cans were more susceptible to fungal attack. Specifically, Primal AC33 showed a level of growth 1; Plexisol P550 40TB, growth rate 3; and Paraloid B72, growth rate 4.

It has been stated several times that synthetic polymers used for conservation treatment can support the growth of microbes and thus be a possible habitat where the conditions that define the niche of the taxon are met (Runeberg, 2008). Indeed, early experiments showing evidence that some fungi were able to grow on a synthetic adhesive, Vinavil Emulsion (polyvinylacetate), were conducted as early as the 1950s at the Istituto Centrale del Restauro in Rome, Italy (Giacobini, 1957; 1958).

2.2. Synthetic polymers change microbial ecology

When biological growth occurs in the added exogenous material, such as the synthetic polymers, a case of extrinsic bioreceptivity according to Guillitte (1995) and quaternary bioreceptivity according to Sanmartín et al. (2021a) is taking place. According to Guillitte (1995) when particles or substances that are not part of the material are deposited and accumulated on the material and the colonisation developed from there no longer relates directly to the properties of the starting material, the bioreceptivity is extrinsic. According to Sanmartín et al. (2021a), when new materials, such as any coating or chemical product leaving residues, are added to the material, its bioreceptivity becomes quaternary. In this sense, the addition of polymers onto a surface may change the physical properties like the wetting-drying kinetics, for example, it may increase the water (and nutrient) retention inside the fissures and voids in the polymeric coating. These cracks also enhance the anchorage of colonizing cells (**Figure 1**), which added to the previous aspect, leads to biofilm formation and, as a consequence, its bioreceptivity increasing (Quagliarini et al., 2018; Sanmartín et al., 2021b).

Paraloid B72-treated and untreated painted specimens from the chapel of the Holy Nail in what is now Santa Maria della Scala Museum, Siena (Italy) showed potential deteriogen taxa in a quiescent state in both, while bacteria were mainly retrieved on untreated samples (Milanesi et al., 2009). This difference in the microbial community demonstrates that bioreceptivity is affected by the presence of the acrylic polymer. The same was true for unpainted and concrete sites with acrylic paint coatings in Georgia, USA, showing that the presence of polymers can affect the microbial ecology (Giannantonio et al., 2009). While studying the Klippe statues, a group of ancient Chinese stone Buddhas in Hangzhou, China, and the feasibility of using synthetic polymers for their conservation, Li et al. (2017) tested lipolytic and ester-hydrolytic activity of the microorganisms they isolated to study potential biodeterioration mechanisms of synthetic materials. Production of esterases was evaluated on mineral medium with added Tween 20®, while Tween 80® and tributyrin were employed as substrates for lipases. Enzymatic tests showed that the majority of bacterial isolates produce lipases while esterases were produced by a few microorganisms.

Unlike in buried environments where wooden materials are barely biodeteriorated because few microorganisms are able to degrade lignin anaerobically (Caneva et al., 2008; Billings et al., 2015), wooden surfaces are easily biodeteriorated in subaerial environments and therefore have been sometimes protected from biological attack with a synthetic polymer (Czajnik, 1968). In research by De Souza and Gaylarde (2002), pinewood was brushed with a transparent alkyd varnish (Tintas Renner, Gravatai, Brazil) and inoculated with fungi, bacteria and algae above or below the coating. The latter case simulated the polymer application over contaminated surfaces and the researchers observed that varying initial contamination could lead to different deterioration results.

Finally, the presence of synthetic polymers can influence how deeply endolithically the microbial community can grow. This is the case of the Grande Albergo Ausonia & Hungaria (Venice Lido, Italy), which has an Art Nouveau tiles on its façade, which underwent restoration in 2007 including treatment with Paraloid B72. On studying the microbial structure of the community, it was observed that when Paraloid B72 was detected, the biofilm was growing in a deeper position than in uncoated specimens (Giacomucci et al., 2011), as also previously reported (Ariño and Saiz-Jimenez, 1996).

2.3. Chemical structure, ageing and application method affect biosusceptibility

In the review by Cappitelli and Sorlini (2008) it was reported that when some polymers were synthesized in the laboratory (with the advantage of having only the polymer to deal with and not the presence of additives), the general order of susceptibility to fungi according to the ASTM G21-96(2002) was alkyds > polyvinyl acetates > acrylics. Investigating the biodegradation of alkyd resins used in household paints and artists' paints, Doménech-Carbó et al. (2008) showed that microorganisms led to the hydrolysis of the polymeric resins with the formation of short-chain fatty acids. In a work by the same team (Doménech-Carbó et al., 2009) microbial biodeterioration of PVA emulsions coincided with the decrease in the relative content of external plasticiser of the phthalate type employed. In addition, a different behaviour was observed, depending on the plasticiser used in each PVA emulsion product investigated.

The paint of a cracked pineapple in the artwork 'Teca con Frutta' by Massimo Zuppelli (1967) was found to be made of cellulose nitrate and alkyd resin (Macro et al., 2020). The paint was deteriorated by fungi, as proven by infrared spectroscopy and scanning electron microscopy. Consequently, conservators applied an antifungal biocide as part of the cleaning treatment. When specific attention was paid to the chemical composition, it was noted that the combined use of acrylic and fluorinated monomers promoted the fungal deterioration of the polymeric material (Sabatini et al., 2018).

Many studies show that these synthetic materials are more bioreceptive (more suitable for biological colonization and its development) when the synthetic polymer is physically and chemically degraded (Cappitelli and Sorlini, 2008). For example, in the acrylic resins of the marble-built Tempio Malatestiano in Rimini, Italy (Pinna and Salvadori, 1999) and the Milan cathedral, Italy (Cappitelli et al., 2007), fungi colonized the synthetic material, rather than lithic material, causing its physical disruption with biopitting and the formation of cracks and fissures (**Figure 2**). Moreover, black fungi were isolated from the Milan cathedral stone and the fungi of the standard ASTM G21-96(2002) method were used to investigate whether the detected poly-isobutylmethacrylate and epoxy resin could be used as the sole sources of carbon and energy (Cappitelli et al., 2007). The freshly dried acrylic resin was susceptible to an isolated *Cladosporium* sp. (Cappitelli et al., 2007). Wall paintings of UNESCO Wu-Kui Tomb in China were treated with acrylic varnish B01-6 applied by spraying to protect them (Sun et al., 2019). On the B01-6 coatings area on the murals seasonally 'white moldy spots' were observed and some microorganisms were identified as novel, e.g. *Leptobacillium muralicola* (Sun et al., 2019). In the dark-gray stone of the Pasargadae World Heritage Site in Iran, lichens were only detected on the areas of the stone where polyester and epoxy resin were employed for conservation treatments (Shekofteh et al., 2018). In the former Czechoslovakia, epoxy resins were frequently employed in sculpture, from the late 1950s for the creation of copies of existing statues, like the Cyril and Methodius installed outside a church in Bratislava in 1989. In research by Pangallo et al. (2015) on these figures, it was seen that the epoxy resins were heavily colonized by fungi, algae and cyanobacteria. Suits from the Apollo lunar missions stored at the Smithsonian Institution's National Air and Space Museum are composed of multiple layers, many of which have begun to degrade. *Paecilomyces* and *Cladosporium* fungi were isolated from two synthetic polymers and were capable of degrading the synthetic polymers themselves, confirming that they were a deterioration factor to consider in the conservation of the spacesuits (Breuker et al., 2003). Danko et al. (2020) reported that in 48 samples from spacesuits subjected to shotgun metagenome sequencing, a diverse microbial population included *Curtobacterium* and *Methylobacterium*.

In addition to ageing, the susceptibility to microbial attack also depends on the way the synthetic polymers have been applied (Borgia et al., 2003; Cappitelli et al., 2006; Cappitelli and Sorlini 2008), the environment, and the amount of product applied (Ferreira Pinto and Delgado Rodrigues, 2014). Four architectural acrylic paints were exposed to outdoor conditions for seven years in both the urban site of São Paulo and the coastal site of Ubatuba in Brazil (Shirakawa et al., 2011). Staining and detachment of coatings were evaluated and the microbial community identified. The painted surfaces were much more discolored in the marine environment, where the principal taxa were the cyanobacteria *Scytonema* and *Gloeocapsa*. These results were related to the higher rainfall in Ubatuba as well as the presence of trees in the marine environment increasing the airborne microbiota. At the Maiji Grottoes on the ancient "Silk Road", China, where PVA emulsion has been applied to protect mural paintings, the enclosed environment was seen as another factor affecting fungal growth (Meng et al., 2020). Indeed, in two grottos that were always kept closed, murals were heavily attacked by fungi. Interestingly, fungal growth was found on the coating and not on the murals, indicating that the synthetic resin was the energy source for microorganisms.

Microbial inhibition conservation strategies are often based on the employment of water repellents to decrease water absorption, hence bioreceptivity, and on the application of biocides (Moreau et al., 2008). One of the few in-situ studies (archaeological stones in Fiesole, Italy), led by Pinna et al. (2018), regarding water-repellents and consolidants (tetraethylorthosilicate, methylethoxy polysiloxane, Paraloid B72 and tetraethylorthosilicate) showed that even when in presence of biocides (tributyltin oxide + dibutyltin dilaurate) and copper nanoparticles, the coatings had no crucial role in preventing microbial development.

3. Biosusceptibility of composites based on synthetic polymers

Polymer composite materials (or polymer composites) have aroused interest for the conservation of cultural heritage and artistic objects. Polymer composites are composed of different unique materials with at least one polymer, tailored for a particular application. They consist of a minimum of two components, the matrix and the reinforcement. The polymer composites show improved physical properties as compared to the individual materials. In this paper, we will refer only to composite materials with synthetic polymers as matrix.

Examples of synthetic polymer composites are fiber-reinforced polymer composites, where carbon fibers are the reinforcements and acrylic polymers, epoxy, vinyl ester, and polyesters are the matrix. These novel polymer composites show interesting properties for the conservation of objects of art, e.g. remarkable physical strength, desired hydrophobicity and optical features, large specific surface area for the absorption of other nanomaterials and appreciable biocompatibility (David et al., 2020).

However, these materials do not escape from being colonized by microorganisms. Recently, Breister et al. (2020) studied the mechanisms underpinning the biodeterioration of polymer composites used in construction and conservation. The researchers combined material investigations with multi-omics analyses to assess the role and mechanisms of biodeterioration of vinyl ester-based polymer composites over time. Six metabolisms that potentially affected the polymer composite structure were identified and associated to taxa belonging to CPR/Patescibacteria, Deltaproteobacteria, Chlorobi, and Chloroflexi, which possess pathways for breaking down the main component of the material such as acrylate, esters, and bisphenol. The degradation of the binding matrix (acrylate, bisphenol A, esters) through chain scission of chemical bonds and the physical damage induced by gas production (H_2S, H_2) contributed to the biodeterioration of the material.

The results presented by van der Werf et al. (2015) showed that only the samples treated with Estel1100 (a silicon-based product employed as consolidant/water-repellent for many lithotypes) and not Estel1100/ZnO nanocomposites, allowed for the growth of the fungus *A. niger*, a ubiquitous fungus on stone substrates, more or less in the same amount as on the bare calcareous stones from the south of Italy.

In order to obtain new stone coatings, two oxides were dispersed in Paraloid B72 and the fluorinated polymer Akeogard CO (Ruffolo et al., 2010). When the two polymer matrices alone were tested for their biocidal properties (5% concentration) on *A. niger* in a few days they were easily attacked. In contrast, in the presence of $ZnTiO_3$ a complete inhibition was observed after a month. *A. niger* was inoculated on treated stone specimens by La Russa et al. (2012) and the microbial development interfered with the structural fabric of the acrylic resin, decreasing its hydrophobicity.

Traditional conservation treatments typically rely on the employment of water repellents to reduce water absorption, and hence bioreceptivity, and on the application of biocides to reduce the colonization process (Moreau et al., 2008). In this respect, polymer composites made with nanoparticles (NPs) and synthetic polymers opened up new opportunities for designing and improving conservation materials of enhanced hydrophobic character (Reyes-Estebanez et al., 2018; Aslanidou et al., 2018) and self-cleaning properties (Crupi et al., 2018; Kapridaki et al., 2018; Ruffolo and La Russa, 2019). An example of polymer nanocomposites is the highly hydrophobic Paraloid B72 coatings obtained by including silica nanoparticles into the acrylic matrix (Ntelia et al., 2020). Polymer nanocomposites offer the advantage of the NPs immobilization within the polymeric matrix, limiting the release of NPs to humans and the environment (Baalousha et al., 2016). Colangiuli et al. (2019) added titanium nanoparticles to a fluorinated polymer for assessing the self-cleaning and photocatalytic features of such a coating over time in a real urban environment. After natural ageing, the coated stone was still protected. However, the photocatalytic efficiency progressively is reduced as result of the loss of the photocatalyst from the coating surface due to a polymer modification by weathering. For this reason, the use of organic binder should be replaced, or at least combined with the inorganic ones.

Recently Aldosari and colleagues (2019) dispersed photocatalyst zinc oxide nanoparticles in the acrylic Paraloid B44 to produce novel polymer composites with effective biocidal, self-protection, and hydrophobic properties, to be used in the protection of deteriorated marble heritage surfaces. Fungal inhibition and self-protection properties were confirmed without any surface colour change. Nanoparticles suspended in Primal AC33 and a silicon polymer applied onto stone reduced by between 61% and 68% the presence of *Escherichia coli*, *Streptomyces parvulus* and *B. subtilis* (Franco-Castillo et al., 2021). Helmi et al. (2015) recommended using Ag nanoparticles for heritage surfaces instead of Cu nanoparticles, due to the stronger colour variation of the latter, but also reported promising antimicrobial activity of Cu nanoparticles, comparable with those of its Ag counterparts, against strains of bacteria and fungi isolated from funeral masks from Saqqara necropolis (Egypt). Similarly, Essa and Khallaf (2014) combined Ag nanoparticles with a silicon polymer, highly reducing bacterial and fungal growth on the coated stones (*S. parvulus* development by 98.6% and the growth of *A. niger* was almost nonexistent). Copper has strong biocidal activity, which is observable when adding an element of this material in a building or structure (see e.g., Sanmartín et al., 2021a). These same authors, Essa and Khallaf (2016) through a novel bioprocess which was inexpensive and eco-friendly, where the embedding of Cu nanoparticles into a polymer matrix led to nanocopper composites with remarkable antimicrobial properties, improved the physical features of the treated stones and also inhibited microbial development on the historical surfaces.

4. Biocleaning to remove synthetic polymers

Besides coming from non-renewable sources, poor compatibility, and appearance changes, synthetic polymers are not readily biodegradable, being difficult to remove and often not re-treatable (Yang and Liu 2014; Mistretta et al., 2019). Traditional conservation techniques for the removal of synthetic resins may lead to more damage compared to uncoated surfaces (Ocak et al., 2015).

As relatively few studies have addressed the biodegradation and biocleaning of synthetic polymers, few microorganisms with the potential to removal those target materials have been identified (**Table 1**). Thus, focusing on the selection of suitable microorganisms is an important area of study. Candidate microorganisms can be found in international microbial collections (DSMZ, ATCC, CECT, etc.) or in natural environments where synthetic polymers are present. Some Vicenza white limestone and veined Carrara marble specimens treated with the consolidant EP2101 (cycloaliphatic epoxy resin) were exposed outdoors for one month and then kept for three months in a box at 24–26°C with 95% relative humidity (Tesser et al., 2018). The dominant fungi that grew on the treated and untreated specimens were identified as *Alternaria alternata,* those developed only on treated stones were *Cladosporium oxysporum* and *Chaetomium* spp. Interestingly, the researchers proposed the use of the fungi identified on the treated specimens for biocleaning.

Fifty-four strains were retrieved from environments where recent and old graffiti were present and their potential ability to attack Montana gold acrylic professional spray paints (shock black, shock red, shock white, ultramarine and R-9011, Montana Colors) was assessed (Sanmartín et al., 2015). Bacteria able to grow on acrylic paints belonged to *Arthrobacter*, *Bacillus*, *Gordonia*, *Microbacterium*, *Pantoea* and *Pseudomona*s and fungi to *Alternaria*. To the best of our knowledge, there is only one other study involving the microbial ecology of graffiti paintwork (Bosch-Roig et al., 2021), where from 31 putative bacteria from naturally aged graffiti, 13 were tested by screening, and three were of interest as they used the graffiti paint as the sole carbon and energy source. Among these, two were identified as the same taxon, the yeast *Candida parapsilosis*, and the other one as the actinobacterium *Rhodococcus erythropolis*. In the study by Cattò and Sanmartín et al. (2021), among the 8 bacteria investigated, *Enterobacter aerogenes* ATCC 13048, *Comamonas* sp. ATCC 700440 and a mixture of *Bacillus* sp., *Delftia lacustris*, *Sphingobacterium caeni*, and *Ochrobactrum anthropi* ATCC 53922 had the highest potential for bioremoval of a black non-metallic spray paint (R-9011, Montana Colors) and a silver metallic spray paint (Silver Chrome, Montana Colors), characterized as alkyd and polyester-based resin, and polyethylene-based resin, respectively.

In the study by Germinario et al. (2017) the removal activity of lipases for acrylic marker pen inks was evaluated. Better performances were shown with the non-aged specimens, suggesting the urgency to perform biocleaning before ageing.

To the best of our knowledge, no bacteria capable of attacking Paraloid B-72 or Paraloid B-44 (by using it as their sole carbon and energy source) have yet been found (Nugari and Priori, 1985; Li, 2006; Troiano et al., 2014). Only the successful use of a *Candida cylindracea* lipase to remove aged Paraloid B-72 from a couple of paintings is reported (Bellucci et al., 1999), but *Candida* strains are not considered safe microorganisms for operators.

5. Final Remarks

One of the most important aspects in the use of synthetic polymers in conservation applications would be the definition of a protocol to test the biodeterioration and the biodegradation (in case of biocleaning procedure) of the materials. So far, most of the studies have been based on testing the impacts and/or performance of single microorganisms. However, these researches do not fully describe the impacts of a complex microbial community on polymeric materials, thus the lack of information on the polymers' biocleaning mechanisms and degradation pathways is not surprising. Moreover, many of the employed microorganisms in prior studies are scarce in molecular surveys carried out in the field and are thus unlikely to be the key drivers of deterioration of synthetic polymers. Therefore, despite the decades of use of synthetic polymers in conservation, little is still known about the diversity and impacts of microorganisms dwelling on synthetic polymers in their heritage context. Test methods should be created based on the practical development of a standard procedure for the qualitative and quantitative evaluation of the durability and removability of the synthetic polymer, to understand under which condition its application can be considered safe for the heritage surface.

The conservation of cultural heritage demands complex interdisciplinary research for developing suitable materials for the protection of heritage surfaces. In the context of synthetic polymers, compatibility with the original material, durability, resistance to adverse environmental conditions, transparency and reversibility/retractability of the treatment are mandatory prerequisites that still represent challenges in conservation practices. For traditional synthetic polymers, such as acrylic and methacrylic polymers, durability and removability is affected mainly by photo-oxidation phenomena (Favaro et al., 2006; Artesani et al., 2020). Thus, the future use of synthetic resins should be seen in a wider and more complex scenario than only the microbiological point of view to assess if, overall, their benefits outweigh the risks and the damage that these materials can pose.

As a consequence of all the above shortcomings of synthetic resins and composites, researchers are now reconsidering the use of natural polymers rather than synthetic polymers to protect heritage from damage and weathering (Ocak et al., 2015; Mistretta et al., 2019). The green chemical approach is driving attention towards biopolymers, especially those from renewable resources. One example is polylactic acid (PLA), which can be produced from lactic acid-derived biodegradable and renewable material (Ocak et al., 2015). Although novel biopolymers are among the most interesting materials for cultural heritage conservation nowadays, their chemical properties and stability over time need to be thoroughly examined. Most of these biopolymer-based solutions are represent only by a single trial, undertaken at the very beginning of the study, but they are nonetheless considered relevant for future investigation.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure 1. Image under stereomicroscope showing the cracks in the coating made of nano-sized silica consolidant containing TiO_2 that served as an ecological habitat for phototrophic organisms. The image was taken from a study conducted by Sanmartín et al. (2021b) and is reproduced by courtesy of the authors.

Figure 2. A view (X40 magnification) of sample 14F035 taken from the Milan cathedral, Italy, in an area where poly-isobutylmethacrylate has been used to protect the marble. Meristematic and sometimes yeast-like growth with budding cells was abundant on this sample (see Cappitelli et al., 2007).

Table 1. List of articles ordered by year of publication, where microorganisms that can be used for synthetic material removal are indicated.

Microorganism	Classification	Role/application	Reference
Candida cylindracea	Yeast	Removal of Paraloid B72 from paintings through a lipase enzyme	Bellucci et al. (1999)
Pseudomonas aeruginosa (PA01), *Pseudomonas stutzeri* (ATCC 23856), *Pseudomonas putida* (DeFENS collection, isolated from wastewater treatment plant), *Escherichia coli* (ATCC 25404), *Bacillus licheniformis* (DeFENS	Bacteria	Four-year dried Paraloid B72, originally solubilized in 15% ethyl-acetate	Troiano et al. (2014)

collection, isolated from a biodeteriorated acrylic painting on canvas by a contemporary artist)			
Arthrobacter oryzae, A. aurescens, Bacillus megaterium, B. aquimaris, Gordonia alkanivorans, Microbacterium oleivorans, Pantoea sp. and *Pseudomona*s *mendocina* and *Alternaria alternata*.	Bacteria and fungi	Acrylic paints	Sanmartín et al. (2015)
Cladosporium oxysporum and *Chaetomium* spp..	Fungi	Cycloaliphatic epoxy resin	Tesser et al., 2018
Enterobacter aerogenes ATCC 13048, *Comamonas* sp. ATCC 700440 and a mixture of *Bacillus* sp., *Delftia lacustris, Sphingobacterium caeni*, and *Ochrobactrum anthropi* ATCC 53922	Bacteria	Alkyd and polyester-based resin and polyethylene-based resin	Cattò and Sanmartín et al. (2021)
Candida parapsilosis and *Rhodococcus erythropolis*	Bacteria	Alkyd and polyester-based resin	Bosch-Roig et al. (2021)

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Figure 1

Click here to access/download;Figure;Figure1.tiff

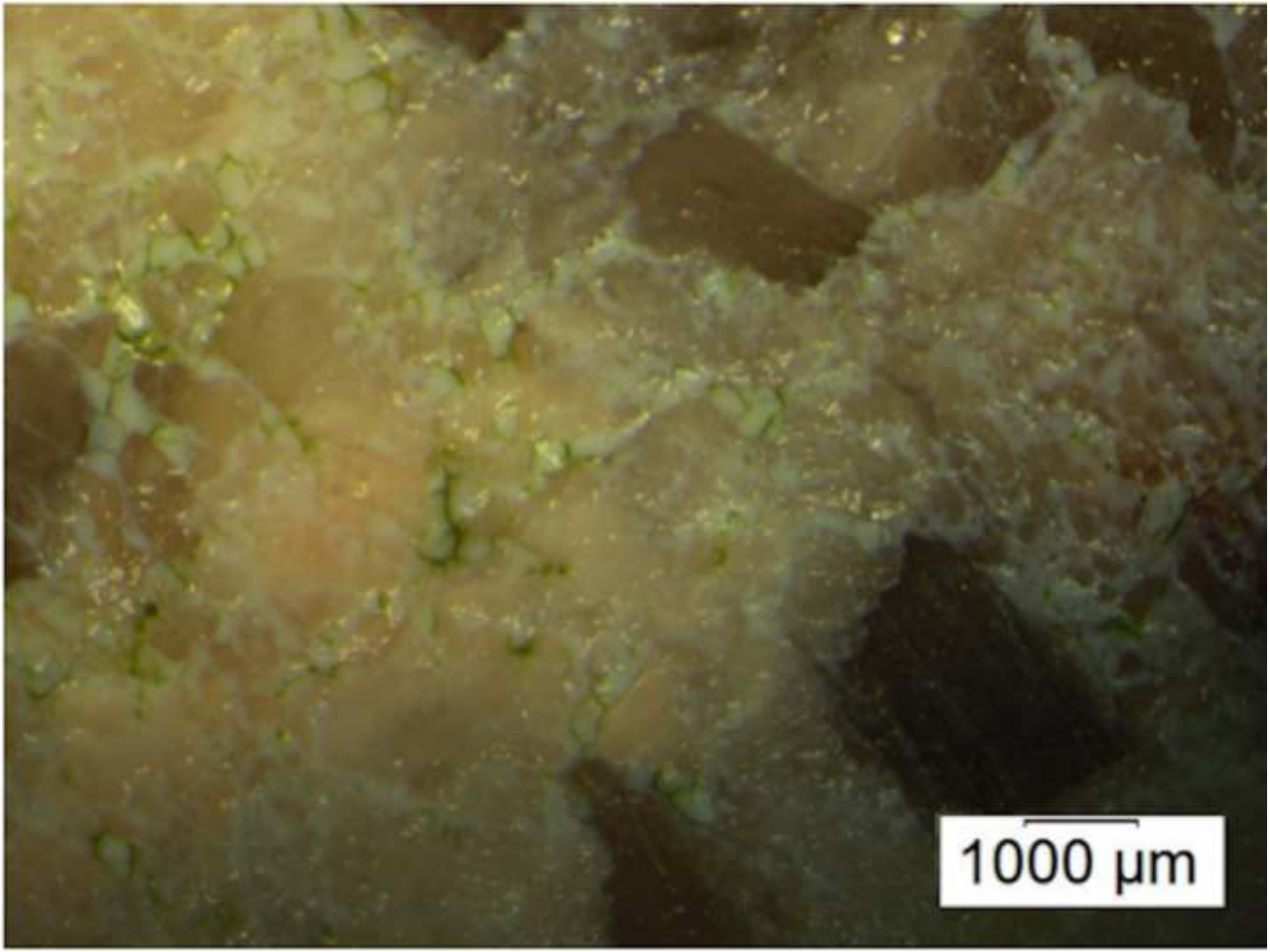

Figure 2.tiff

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Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: