Biodeterioration of Stonework

Sir: Why are old marble statues rough when new marble floors are smooth?

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Biodeterioration of Stonework

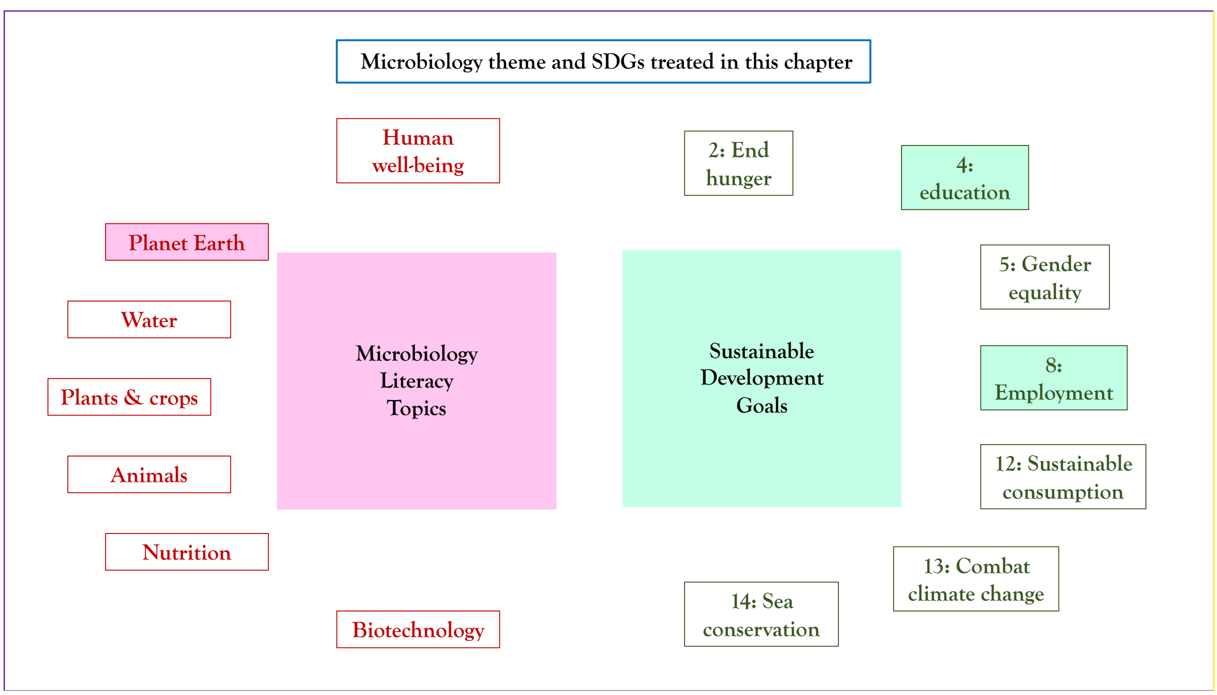
Storyline

Children living in big or small cities, or even in rural areas, are surrounded by outdoor stone-made items, monuments and buildings which, although the children may not realize it, look different from the time when they were built or installed. Children can exhibit curiosity about what changed the rock from what it looked like when it was extracted from the quarry to its present appearance. Just noticing the color and texture of the present surface, compared with a new or well-preserved object, leads to questions like the one in the title. Climate, pollutants, and human activity can speed the microbial deterioration that causes color and texture changes. Microorganisms are a powerful tool of nature that play a crucial role in the geobiological cycles of inorganic and organic compounds that make these changes.

Most marble works of art are part of our cultural or historic heritage and for this reason there is a need to preserve them for the future generations. Different actors including microbiologists at various levels (individual, local community, and government) are involved in the conservation of stone cultural heritage.

The Microbiology and Societal Context

The microbiology: microbe:mineral interactions; biofilms: patina; biomineralization; biodeterioration; bioconservation. *Sustainability issues:* education; employment.



NB: this topic is ideally delivered together with a class excursion that explores microbial growth on rocks, buildings and monuments.

Biodeterioration: the Microbiology

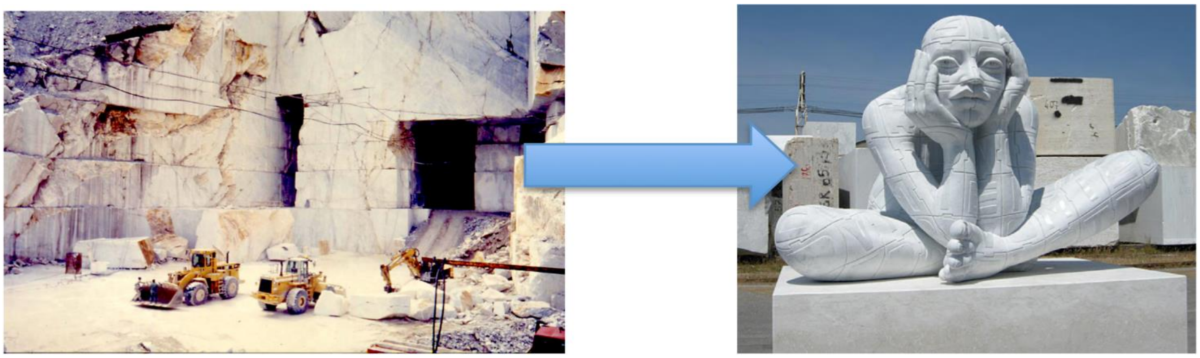
1. From the quarry to cultural heritage. Since antiquity, many kinds of stone and marble have been used by humans for different purposes: to make statues, decorative elements of buildings, floors and objects of common use. As is the case with natural rock, processed smooth marble surfaces become rough and may even crack when exposed to climatic events, pollution and neglect. In addition, both can be attacked by various organisms, including those invisible to the naked eye (microorganisms). The use of terms “biodegradation” and “biodeterioration” allow us to define an identical process that occurs in nature, as well as to objects of economical, cultural heritage historic value.

Natural rock formations are classified by the geologists on the basis of their genesis and composition. In particular, marble originates from sedimentary rocks that underwent changes in the geological era (millions/billions of years ago) due to high pressure and temperature causing the transformation of its main constituent, calcium carbonate, into a crystal form called calcite. As part of the carbon cycle, carbonate is also formed by autotrophic and heterotrophic microorganisms by the process of biomineralization.

Natural stone reservoirs are found in mountains or flat lands; when they are exploited to obtain stone blocks, they are termed quarries.

Carrara quarry in the Apuan Alps (Italy).

Since antiquity, skilled workers are needed to quarry stones such as marble, to obtain blocks of good quality suitable for different uses. Carvers process the stone blocks working from the general to the specific; however different approaches can be used depending on the personal preferences, training, the material being carved or the desired effect.



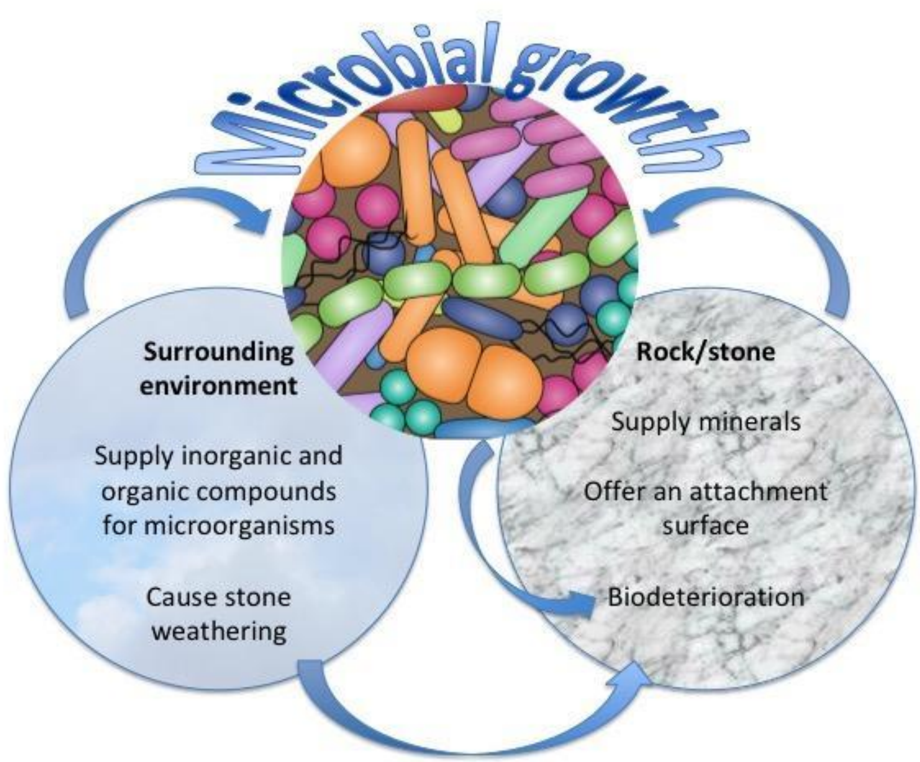
On the left: Marble quarry (Carrara, Italy; photo C. Urzì); on the right: a modern Carrara marble statue called Lettere implose 2011 (Courtesy of the Artist Rabarama and Telara Studio d'Arte, Carrara, Italy).

2. ***Can microorganisms grow on natural rocks and stones?*** Similar processes of biological colonization can occur on rock as well as on stone-built items exposed outdoors. The consequent pattern of alterations can be described as biological patina, spots, or biopitting, depending also on the horizontal or vertical orientation of the surface.

Similar pattern of colonization of: a) a rock covered by various organisms (mosses, algae, fungi, lichens) in the Davison Park, Michigan (photo C. Urzì); b) a tombstone in the old Collins cemetery in Michigan exhibiting a black biological patina produced by algae, lichens and fungi (photo S. Collins); c) a statue in the presidential Quirinale garden (Italy), covered by a black biological patina produced by algae and fungi (photo S. Ricci).

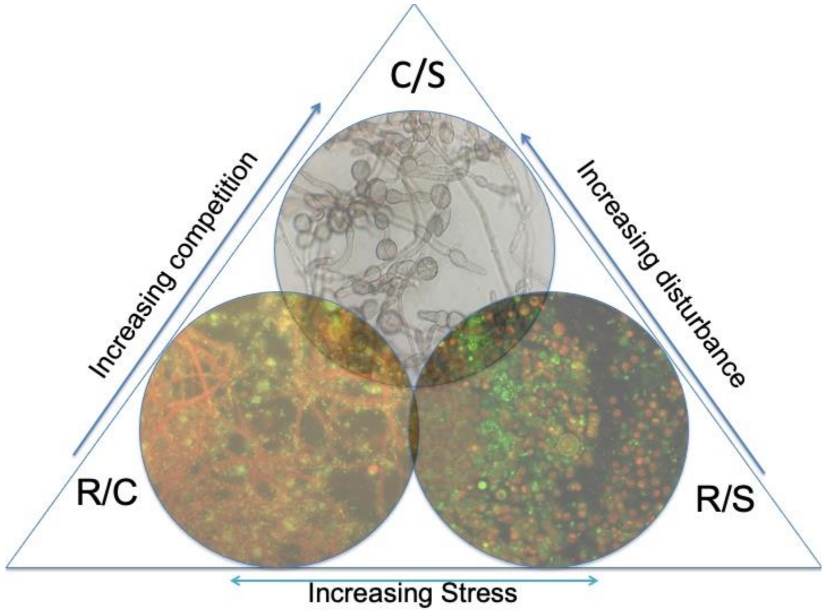
Why? Rock surfaces offer a good support for the attachment of microbes and supports their survival and expansion. Microbial cells adhere to rocks by forming a biofilm – a sticky matrix of extracellular materials containing the microbes – that provides the cells within with protection against noxious environmental stresses. Colonization can occur on the surface of rocks as spots or as diffuse biological patina (see images above), or inside the rock due to penetration by bacteria, algae and especially fungi that cause biopitting, or inside the rocks through invasion of existing cracks.

Carbonate is solubilized and used as carbon source by euendolithic algae/cyanobacteria that secrete organic acids, followed by release of CO2 that is promptly used. Rock thereby becomes more porous and favours the deposition of dust, salts and organic debris that supports the growth of other microorganisms. As consequence, the stone bioreceptivity – its ability to support the growth of other organisms – increases and becomes prone to support the growth of higher organisms, such as mosses. Thus: bacteria, algae, cyanobacteria and fungi play an important role in rock surface deterioration, through the formation of a biofilm on the surface, acid release, and mechanical movement into the stone.



Interactions of stone, microorganisms and the surrounding environment.

Microorganisms can be classified according to their ecological needs, distribution, and chance of survival, in C (competitors), S (stress tolerators) and R (ruderal). Most of the microorganisms that colonize stones fall in more than one category. For example, black meristematic fungi can be found as sole colonizers on the rock surface, due to their high tolerance to climatic stresses (UV, temperature, drought), while black hyphomycetes can be considered competitors due to their resistance to stresses but also by their fast growth.



Competitor-Ruderal-Stress tolerator life strategy framework as was proposed for plants and adapted to microorganisms. The CSR framework identifies three main life strategies: (C) competitors are adapted for rapid resource use and long-term site occupation, (S) stress tolerators are adapted to persist in low-resource environments owing to resource-conservation strategies, and (R) ruderals cope with frequent disturbance by relying on high colonization ability.

3. ***Conservation of stone-built items.*** Stone objects find their different destinies outdoors (public places, gardens, cemeteries, etc.) or indoors (museums, buildings, houses, etc.). Different actors are in charge of their maintenance, and the conservation of stone objects and buildings can be summarized in the acronym SMART:

Sustainability: conservation as an engine of local development, with the cultural heritage linked to the aspects of the local context in which it is found.

Management: planning conservation from restoration into the present and future, and accounting for the health of the operators and environment.

Actors: people including volunteers, tourists, students, businesses, and such heritage professionals as museum employees, archeologists and scientists including microbiologists.

Risks: resilience, loss of economic resources, loss of integrated and specific skills.

Tools: innovative materials and methods.

At which stage is microbiology involved? Microbiology applied to the conservation of cultural heritage is involved in four different stages:

a. Understanding the reason why microorganisms found a suitable substrate to grow, e.g. water and nutrient availability, previous treatments, pollutants and dust deposition.

b. Assessing the involvement of microorganisms in the deterioration of stone. This stage considers different skills that must be possessed by the microbiologist in charge: i) definition and description of the alterations that can be attributed to the microbial colonization; ii) use of non-invasive, non-destructive sampling tools; iii) appropriate multistep investigations that include microscopy, cultural analysis, biochemical tests, molecular-based techniques, etc.

c. Testing conventional and/or new treatments and suggesting the most suitable in laboratory tests, as well in the field.

d. Adopting biotechnology solutions. Microorganisms with certain metabolic patterns can be used for cleaning or for consolidation processes (bioremediation).

4. *Stone cultural heritage and microbiology*

a. Interactions of microbes and stones. Microbiology applied to rock and built stones is a branch of environmental microbiology because it considers stones of historical and cultural heritage as a special habitat in which microorganisms grow. Geographical position, status of conservation, religious beliefs and other factors can enormously affect the microbial colonization and in turn the conservation.

The evaluation of actions of microorganisms on the stone faces different aspects and different questions can be raised: Are there microorganisms? What kind of microorganisms? Are they biodeteriogens? How do they affect the stone/monument perception and durability? The answers are obtained through: i) the determination of the presence and type of microorganisms involved by the description of alterations, ii) the use of different techniques to identify microorganisms, and iii) the demonstration of their effect on the stones.

Can pollutants have an effect on colonizing microorganisms? Organic and inorganic pollutants may have an enormous effect on the microbial colonization of stone by inhibiting the growth, selecting the type of microorganisms that can take advantage of the stone substrate, or even enhancing their growth. Biochemical activities and cooperation among functional microorganisms occurs especially in the biofilm, where mineral nutrients and anthropogenic pollutants are assimilated and metabolized through biogeochemical cycles.

b. Can we stop the colonization? Before any biocidal treatment is applied on valuable surfaces, they need to be tested in laboratory conditions in order to choose the most effective. New biocides should be tested to characterize not only their efficacy but also what actions are needed to apply them. For instance, is it necessary to remove already existing biomass or just to apply the biocide. If a new biocide will be applied, antifouling coatings should be carefully planned

c. Can microorganisms be used for cleaning or protecting stone surfaces? Bioremediation-based biotechnology uses microbes for conservation purposes, due to their great metabolic plasticity. There are two approaches currently in use: i) to use microorganisms for cleaning purposes e.g. to remove sulfates, nitrates or organic substances; bioremediation offers advantages over chemical and physical methods because it is selective towards specific compounds, and ii) to reinforce/consolidate carbonaceous stone through the process of biomineralization. Bacterially-induced carbonate precipitates can be considered as an eco-friendly approach and can be applied *in situ* as suspension or inserted into materials for conservation (such as mortars) that could contain quiescent microbes that will be activated when cracks are formed and water enters in depth.

5. ***Stone Cultural Heritage: The Microbiology and Societal Context***. Conservators/restorers involve microbiologists to solve problems of unwanted colonization causing biodeterioration. The solutions they may propose to the conservators are dependent on the level of analysis that can be reached and the problem faced. Often, it is the budget availability that decides the level of answers that can be obtained. National and local governments of Cultural Heritage, private sponsors, etc. may be the financial sources for conservation activity in which biodeterioration is also involved. Regular monitoring and maintenance should be preferred over the urgent intervention.

Everyone should be aware that if microorganisms are growing well, it indicates that the status of conservation of the object is very bad. Non-microbiologists first see damage by microorganisms when their moderate or extensive growth changes/reduces the visibility of the surface, making it difficult to read a script or to perceive an ornament.

6. Monuments and communities

a. Individuals. Individuals can be involved as guardians of monuments. In fact, UNESCO World Heritage Centre (WHC), in collaboration with the Coordinating Committee for International Voluntary Service (CCIVS), supports individuals to preserve natural and cultural sites, as well as to raise awareness among local communities about their heritage, offering opportunities to young people to go to some of the most outstanding places in the world. Individuals can be involved through the use of dedicated apps to interact with experts, filling a form and sending pictures of the site visited (e.g. Rock Art CARE https://rockartcare.ncl.ac.uk to develop resources to aid the protection of open-air rock art in the United Kingdom and Ireland and beyond). Expanding the use of apps can help to educate visitors and to make them more aware of the risks faced by our cultural heritage.

b. Community. Another action that can be useful to increase the bond between our past and a sense of membership is the adoption of a monument, to protect it against neglect and damage. This action is found in several countries (Italy, Ireland, Germany, etc.), especially in small villages in which the local community becomes actively involved in the conservation and interpretation of heritage sites in their local area. This may contribute to i) the community development, ii) boosting tourism, business and employment opportunities; iii) developing and understanding the story of the place where the community is living. In large cities, schools can involve their students in a similar way, to develop persistent awareness of protecting cultural heritage.

c. Government. Governments should invest in projects regarding conservation of Cultural Heritage or historic buildings, due to the impact on tourist and recreation activities. In addition, visitors' expenditure generates income for the local communities and infrastructure development. It is reported that in Europe tourism and recreation activities are estimated to contribute € 415 billion to the EU GDP, and 3.4 million tourism enterprises account for 15.5 million jobs (European Commission 2014).

d. Private sponsors. Conservation projects can also be financed by private sponsors. Potential sponsors must be chosen and educated to understand how microbiological issues are to be considered for optimal preservation of Cultural Heritage objects in which they may be interested.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 4. Ensure quality education and lifelong learning opportunities.** Our cultural heritage educates us about the past, especially about our cultural roots, inspires us to learn more about history, art, politics and so forth, and stimulates us to be creative ourselves. It is therefore a pivotal educational resource for schools and adults alike. Conserving our cultural heritage, by counteracting microbial biodeterioration activities, and employing microbes to repair and preserve it in good condition, thereby contributes to education.
- **Goal 8. Promote economic growth and employment.** Cultural heritage sites represent important tourist destinations and hence are sources of employment. Conservation of the items on show prevents lowering of interest and thus maintenance of employment.

A child-centric microbiology education framework

Potential Implications for Decisions

1. ***Individual***
   - **a.** Should I go to see local and regional cultural heritage items, and learn about history and artistic developments, or play games on my console?
   - b. How often should I make the effort to see my cultural heritage, and those of others?

2. ***Community policies***
   - **a.** Information and educational campaigns on local cultural heritage.
   - **b.** Encouragement of school visits to local cultural heritage sites
   - **c.** Support of local cultural heritage site restoration work
   - **d.** Support of local cultural heritage site tourist development

3. ***National policies***
   - a. Policies to ensure that items and sites of cultural heritage of national importance are properly conserved and protected for future generations
   - b. Financial support for conservation of cultural heritage of national importance
   - c. Financial support of conservation efforts of local authorities

Pupil Participation

1. ***Class discussion of how microbes impact cultural heritage***

2. ***Questions that children may ask the teacher***
   - a. Are there microbes on shiny surfaces?
   - b. If you just look at rocks and stones near you, do they have microbes on them??
   - c. What does a microbe look like? Is it any special color?
   - d. What is the effect of the pollutants for the marble and for microorganisms?
   - e. Can we stop/reduce colonization?
   - f. Can microorganisms be used for the conservation?

3. ***Pupil stakeholder awareness***
   - a. Do you think it is important to consider what is happening to your cultural heritage now in terms of what it may be like for your own children?
   - b. Do you think you should join a citizen's cultural heritage conservation group to help conserve local items?

The Evidence Base, Further Reading and Teaching Aids

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