https://doi.org/10.5194/egusphere-2024-2758
Preprint. Discussion started: 12 September 2024

Study on the Biological Communities and Bioweathering of Marble Surfaces at Temple of Heaven Park, Beijing, China

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Abstract: This study examines the biological communities on the marble surfaces of the Temple of Heaven Park, Beijing, China and finds that the dominant populations are aerophytic cyanobacteria (blue-green algae) that prefer calcareous environments, are drought-resistant, slow-growing, and extremely resilient. These aerophytic cyanobacteria on the marble surface of the Hall of Prayer for Good Harvests in the Temple of Heaven exhibit different population compositions depending on the orientation. On the east-facing, warm and humid rock surfaces, the biological communities are mainly composed of small filamentous algae and spherical algae, such as *Scytonema bohneri* and *Gomphosphaeria* sp. On the west-facing, hot and humid rock surfaces, the biological communities are mainly composed of small filamentous algae and mosses, such as *Scytonema millei*. On the north-facing, cold and humid rock surfaces, the biological communities are mainly composed of spherical algae, such as *Myxosarcina* sp. and *Gomphosphaeria* sp. On the south-facing, hot and dry rock surfaces, the biological communities are mainly composed of small filamentous algae or large filamentous algae, such as *Scytonema myochrous* and *Nostoc calcicole*. The biological communities in the study area display various colors, with grayish-black being the most common, followed by grayish-white, black, brown, and blackish-brown. The grayish-black communities are primarily composed of *Myxosarcina* sp. and *Gomphosphaeria* sp. The rock surface biological communities exhibit different morphologies, including membranous, hairy, carpet-like, leathery, shell-like, and powdery layers. Different morphological communities have different population compositions. The growth and distribution of aerophytic organisms on the rock surfaces are closely related to the smoothness and texture of the marble. On uneven or non-uniform marble surfaces, aerophytic communities appear in spots, forming solution pits, cavities, and depressions. On surfaces with linear patterns or non-uniform textures with joint stripes, the communities form linear distributions, resulting in solution marks, grooves, and channels. On smooth, uniform marble surfaces, the communities spread evenly, leading to weathering layers or exfoliation. The mechanism of biological dissolution involves aerophytic organisms secreting organic acids,

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which dissolve inorganic salts from the rock to obtain nutrients. This process "erodes" the rock, damaging its surface structure and gradually weathering it. Given the prolific growth of aerophytic organisms on marble surfaces, finding ways to prevent or reduce their growth is crucial for slowing down the weathering process of stone cultural relics in the Temple of Heaven Park.

Keywords: Temple of Heaven Park, Beijing, China; marble; aerophytic algae; cyanobacteria; bioweathering.

1. introduction

The Temple of Heaven Park in Beijing，China, completed in the 18th year of the Yongle reign of the Ming Dynasty (1420), has a history of 604 years to date. It is the largest existing ancient sacrificial building complex in the world, where emperors of the Ming and Qing dynasties performed ceremonies to worship heaven and pray for good harvests. In 1961, the State Council of China declared the Temple of Heaven a "National Key Cultural Relic Protection Unit." In 1998, it was recognized as a "World Cultural Heritage" site by UNESCO. The Hall of Prayer for Good Harvests is the core structure of the Temple of Heaven Park and was the venue for the Qing Dynasty's grain prayer ceremonies. It consists of an upper building and a lower terrace. The building is the Hall of Prayer for Good Harvests, while the terrace is a three-tiered circular platform. Each level of the circular platform is surrounded by white marble railings with bluish-white stone foundations. The upper level's corner columns are decorated with coiled dragons and water spouts with chi-dragon heads. The middle level's corner columns feature flying phoenixes with phoenix-head water spouts. The lower level's corner columns are adorned with cloud motifs and cloud-shaped water spouts. Most of these white marble and bluish-white stones originate from the marble quarries in Dashiwo Town, Fangshan District, Beijing (Wu and Liu, 1996; Lü and Wei, 2020). Among the various stone materials used for cultural relics, such as granite, marble, sandstone, limestone, and conglomerate, marble is the softest and most easily weathered. The white marble, in particular, is even softer and more prone to weathering (Ye and Zhang, 2019). However, white marble is pure white, solid yet fine-grained, and easy to carve. It is often used for intricate carvings such as palace railings, imperial steps, and various stone tablets, making it a highly prized building material. Bluish-white stone is generally chosen for load-bearing components like pedestal stones, cap stones, stone bridges, and slabs. White marble and bluish-white stone became the most favored stone materials for royal constructions, but they are also the most susceptible to

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weathering among stone cultural relics.

Marble, when exposed to natural environments over long periods, not only endures physical and chemical weathering but also undergoes biological weathering. Biological weathering refers to the degradation caused by biological activities, which impacts the rock through growth and activity of organisms. This process not only alters the physical and chemical properties of the marble surface but also leads to the formation of unique biological communities, primarily aerophytic cyanobacteria. Chinese scholars have conducted numerous studies on the physical and chemical weathering of marble (Liu et al., 2005, 2006; Liu, 2007; Wang, 2010; Zhang et al., 2013; Zhang et al., 2015; Yang, 2016; Zhang et al., 2016; Qu, 2018; Zhao, 2018; Beijing Ancient Architecture Research Institute, 2018; Ye and Zhang et al., 2019; Liu, 2020; Shu, 2020; Wang et al., 2020; Zha, 2021; He, 2021; Zhang, 2022; Li, 2023; Wang, 2023; Wang et al., 2024). There have been numerous studies on the biological weathering of rocks worldwide. Research on Roman marble monuments has shown that dark spots indicate the presence of cyanobacteria. This biological activity promotes particle detachment and accelerates weathering, leading to pit formation. In Trajan's Forum, the estimated rate of pit formation is 1 millimeter every 40 years. To prevent biological corrosion of limestone and marble monuments, the habitats and ecological needs of various microorganisms must be considered (Danin and Caneva, 1990). Microorganisms can spontaneously remove particles from stone surfaces, causing corrosion of building materials (Praderio, et al., 1993). Humid climates and air pollution make biological corrosion more destructive (Warscheid, et al., 1996). Bryophytes can corrode rock substrates through biogeochemical and biogeophysical mechanisms (Altieri and Ricci, 1997). Studies on stone monuments from Angkor, Maya, and Inca civilizations have found lichens, cyanobacteria, fungi, and bacteria to be ubiquitous. The main causes of stone erosion are organic and inorganic acids (sulfuric and nitric acids) produced by microorganisms, as well as sulfur cycling and oxidation (Zhang et al., 2019). Microbial communities form biofilms that cover the surface of building stones, adapting to the limited nutrient and water conditions for growth. These biofilms create colored biological coatings that cause aesthetic damage to the building stones and alter the structural properties of the materials. They can even promote "non-biological" corrosion processes through mechanical pressure caused by the shrinking and swelling of the colloidal biofilms, leading to further weakening of the mineral lattices. Acid decomposition and redox biocorrosion processes result in the formation of harmful crusts on the building stones (Warscheid and Braams, 2000). In the Yunnan Stone Forest of China, which consists of extremely pure carbonate rocks,

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biological community corrosion can control the formation of some small-scale features (Tian et al., 2004). A laboratory study using rock samples from Portugal showed that microalgae and cyanobacteria grow easily on limestone but little to none on granite (Miller et al., 2006). A study of 249 samples from 83 different locations in the Mediterranean found that cyanobacteria were the most common biocorrosion organisms (Lombardozzi et al., 2012). The Pyramid of Caius Cestius in Rome, a funeral building constructed between 272 and 279 CE, is covered with marble that has developed a gray-black microbial crust, primarily consisting of spherical and filamentous cyanobacteria of the genera *Chrococcus*, *Gloeocapsa*, and *Tolypothrix*, as well as green algae, fungi, and lichens (Golubić et al., 2015). Some researchers believe that prokaryotes, fungi, micro-animals, and plants form an ecosystem that collectively participates in the biocorrosion process of rocks (He et al., 2022). Microorganisms form a biofilm layer on rock surfaces. This biofilm is a metabolic cooperative network that achieves optimal utilization and recycling of the substrate, decaying plant and animal matter, animal feces, and other substances deposited from the atmosphere onto the surface (Liu et al., 2022). Some researchers believe that cyanobacteria primarily corrode stone, while bacteria, archaea, and fungi mainly corrode metals (Gaylarde and Little, 2022). Recent studies have found high microbial diversity on marble surfaces, characterized mainly by cyanobacteria, proteobacteria, and Deinococcus-Thermus (Timoncini, 2022).

This paper primarily analyzes the community composition, structure, and relative biomass of biological communities on marble surfaces. It aims to identify the relationship between the distribution of biological communities and the characteristics of marble surfaces, as well as to reveal the relationships and mechanisms between the development process of biological communities and their biocorrosion processes.

1 Overview of the Study Area

Beijing is located in a warm temperate semi-humid monsoon climate zone, characterized by a cool mountainous climate. The average annual temperature in the region remains stable at 10.8°C, with a frost-free period of approximately 150 days. In winter, Beijing is influenced by cold currents from the northwest, resulting in a cold and dry climate with prevailing northwest winds and an average annual wind speed of 1.9 meters per second. During summer, the influence of tropical high-pressure systems leads to hot weather with concentrated rainfall, particularly from July to September, which accounts for 85% of the annual precipitation, often occurring as heavy rainstorms. Beijing typically experiences pleasant autumn weather,

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while spring is relatively short. The frost-free period ranges from 190 to 200 days. Under extreme weather conditions, summer temperatures can reach up to 42°C, while winter temperatures can drop to -25°C. The monthly average temperature and precipitation in Beijing from 1995 to 2015 are shown（Fig. 1）(Yang, 2016). The annual precipitation in the Beijing area fluctuates significantly, ranging from 255.6 to 1316.3 millimeters, with a multi-year average precipitation of approximately 579.3 millimeters. Through linear trend fitting observation, from 1951 to 2011, the precipitation shows a decreasing trend, with an average annual decrease of about 3.4 millimeters (Fig.2) (Li et al., 2014).

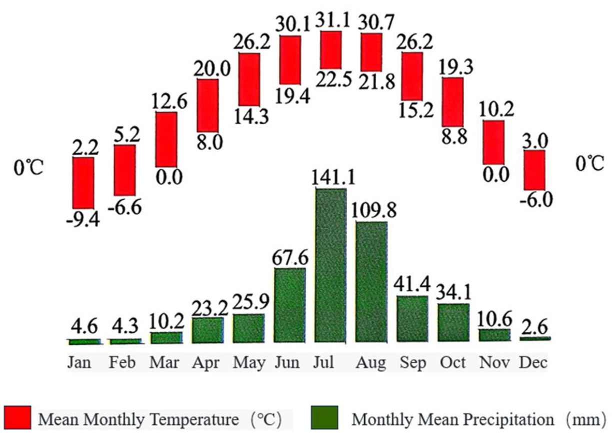

Fig. 1. Monthly average temperature and precipitation in Beijing, China from 1995 to 2015. (Yang, 2016)

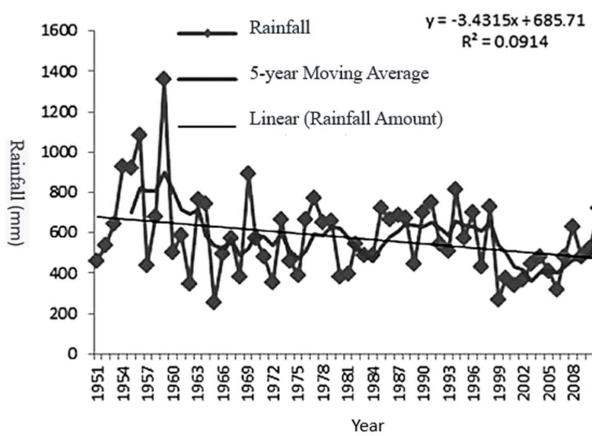

Fig. 2. Interannual variation trend of precipitation in Beijing, China from 1951 to 2011. (Li et al., 2014)

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The main production area of Beijing marble is Dashiwo Town, located in the southwestern part of Fangshan District, Beijing. In Dashiwo Town, the blue-white stone was the earliest to be mined due to its relatively shallow burial depth. The white marble, on the other hand, is buried deeper and is typically the deepest layer among the stone strata, with a thickness ranging from 90cm to 150cm. In the construction industry, both white marble and blue-white stone are widely used marble materials.

2 Research Methods

2.1 Field Work

Algal communities of different morphologies were collected from marble surfaces and placed in specimen boxes. These were numbered, photographed, and their appearance, color, and morphology were described, along with the date and location of collection. The micro-morphologies formed by the dissolution of algal communities were observed and photographed. A total of 40 algal community specimens were collected in the field, and 22 field photographs of algal communities were taken.

2.2 Laboratory Work

2.2.1. Microscopic Observation

A stereomicroscope (Szx7, Olympus, Japan) was used to observe the size, morphology, and color of the algal communities. Then, temporary slides were prepared from algal communities of different colors and observed under a biological microscope (Bx51, Olympus, Japan). The genera and species of algae were identified (using reference books such as Desikachary, 1959; Geitler, 1932; Komarek, 1998; Zhu, 1991; Fudi, 1980; Hu and Wei, 2006), and photographs were taken. In the laboratory, one microscope slide was prepared for each lower plant ecological specimen number, totaling 40 lower plant microscope slides. A total of 142 microscopic photographs were taken.

2.2.2. Biomass Statistics

The volume percentages of algae were recorded. These volume percentages were statistically analyzed to calculate the relative volume (Vx, relative biomass). The statistical and calculation methods are as follows:

(1) Relative Volume (V_x, Relative Biomass)

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For each microscope slide, the percentage of volume occupied by each species of lower plant relative to the total volume of lower plants on that slide was estimated (on the slide, the larger the area occupied by a species of lower plant, the greater its volume). This gives the estimated volume percentage (v(x)%) for that species of lower plant on that slide. The volume percentages for the same species of lower plant across all slides in the study area were then summed to obtain the relative volume for that species in the study area. The relative volume of a lower plant reflects its relative biomass in the study area. It is not the actual volume but is an estimated relative value, only meaningful for comparison purposes.

$$V_x = v(x)_{i_1} + v(x)_{i_2} + \cdots + v(x)_{i_n}$$

i_n represents the microscope slide number; x represents a specific species of lower plant; $v(x)_{i_n}\%$ represents the estimated volume percentage of the lower plant x.

(2) Relative Volume Percentage (Y_x, Relative Biomass Percentage)

This is the percentage of the relative volume of one species of lower plant in relation to the sum of relative volumes of all lower plants in the study area. It is also referred to as the relative biomass percentage.

$$Y_x = \frac{V_x}{n \times 100} \times 100\%$$

n represents the total number of microscope slides.

The relative volume percentage, also known as the relative biomass percentage, does not represent the actual biomass. This is because it is currently very difficult to accurately measure the biomass of microorganisms on marble surfaces. Through microscopic observation and estimation, we can roughly understand the growth conditions of microorganisms. It is a relative value and only has comparative significance.

3 Results

3.1 Population Distribution Across the Entire Study Area

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The biological composition on the marble surface in the study area is shown (Fig. 3). A total of 30 genera and species were identified. The most abundant species is *Myxosarcina* sp., followed by *Gomphosphaeria* sp., *Asterocapsa atrata*, *Gloeocapsa crepidinum* (Fig. 4), and *Scytonema millei*, among others. These species are common aerophytic algae found on limestone rock surfaces (Tian et al. 2002, 2003, and 2004). They thrive in calcareous environments, are drought-tolerant, grow slowly, and possess extremely strong vitality.

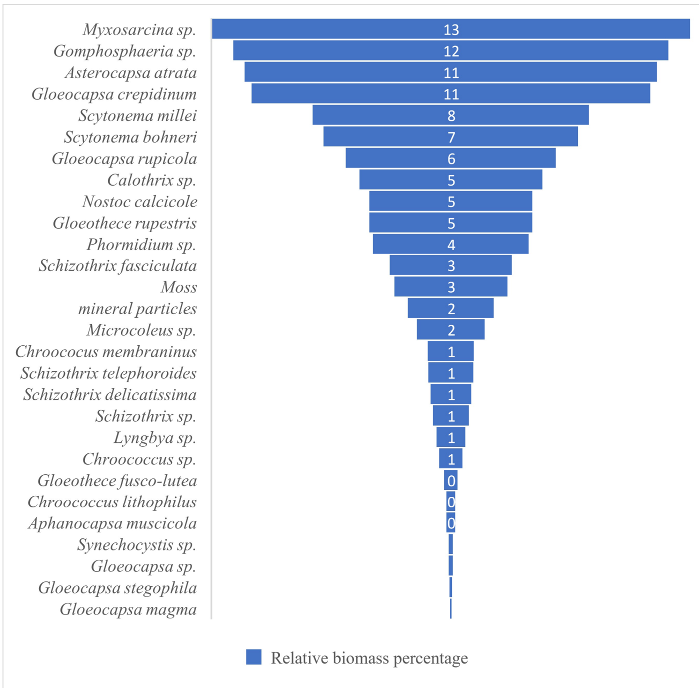
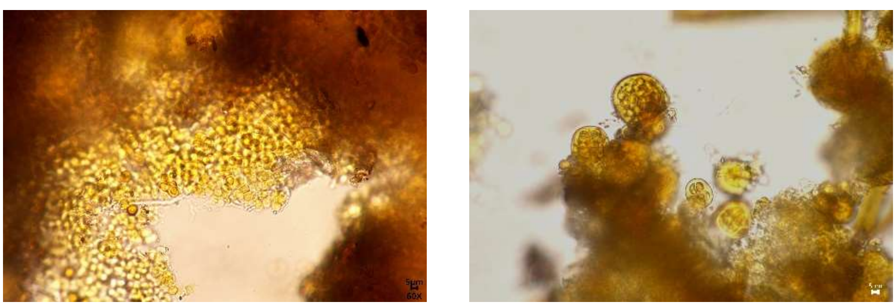


Fig. 3. Relative biomass percentage of marble surface in Beijing Temple of Heaven Park，Beijing, China.



a. *Myxosarcina* sp. **b.** *Gomphosphaeria* sp.

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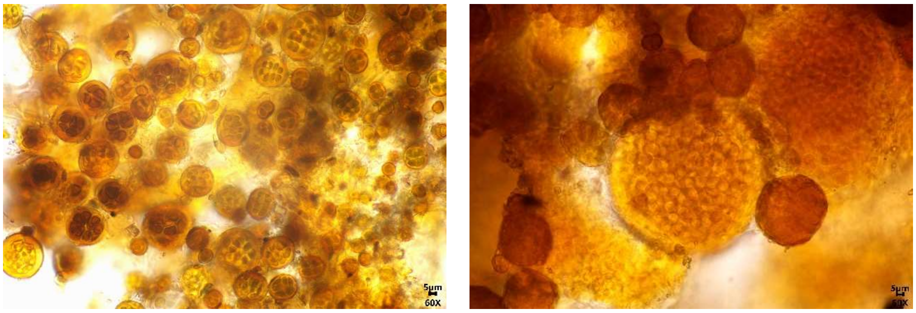

c. *Asterocapsa atrata* **d.** *Gloeocapsa crepidinum*

Fig. 4. Dominant Organisms on the Marble Surface of the Temple of Heaven in Beijing, China.

3.2 Characteristics of Biological Population Distribution on Marble Surfaces with Different Orientations in the Study Area

The Hall of Prayer for Good Harvests in the Temple of Heaven Park is a circular building. Marble surfaces with different orientations receive varying amounts of sunlight exposure. The south-facing surface receives the longest duration of sunlight, followed by the east and west-facing surfaces which receive half-day sunlight, while the north-facing surface is shaded and receives no direct sunlight. This variation in sunlight exposure leads to changes in the biological populations on the rock surfaces. The following sections will discuss these variations separately:

3.2.1 Characteristics of Biological Populations on East-facing Rock Surfaces

The biological communities on east-facing rock surfaces are primarily characterized by gray-white, gray-brown, brown, gray-black, black-brown, white, and black-brown leathery appearances. The main species include *Scytonema bohneri*, *Chlorococcum* sp., *Gloeocapsa rupestris*, *Gloeothece rupestris*, *Myxosarcina* sp., *Phormidium* sp., *Calothrix* sp., *Gloeothece crepidinum*, *Lyngbya* sp., *Gloeocapsa compacta*, and *Chroococcus membraninus*（Fig.5）. Among these, the dominant species are *Scytonema bohneri* and *Chlorococcum* sp., accounting for 25% and 23% of the relative biomass percentage（Fig. 6）. *Scytonema* is a very common genus among aerophytic algae (Tian et al. 2002, 2003, and 2004).

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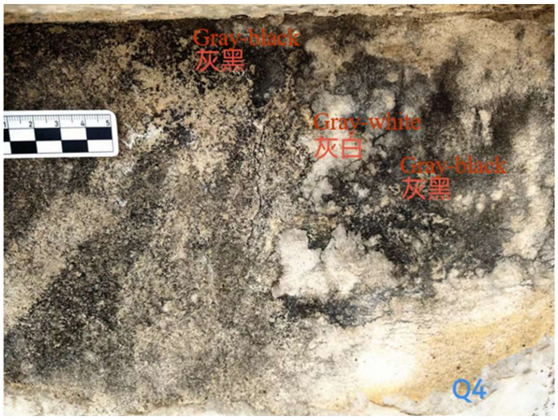
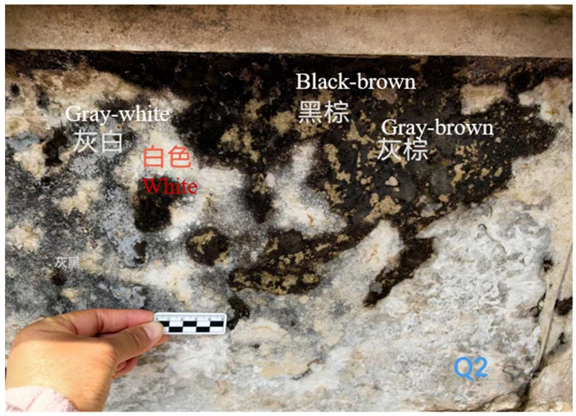
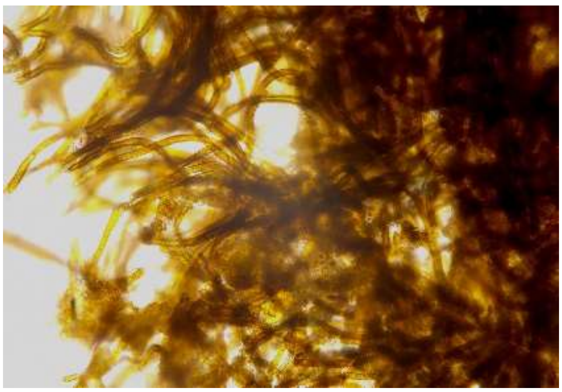


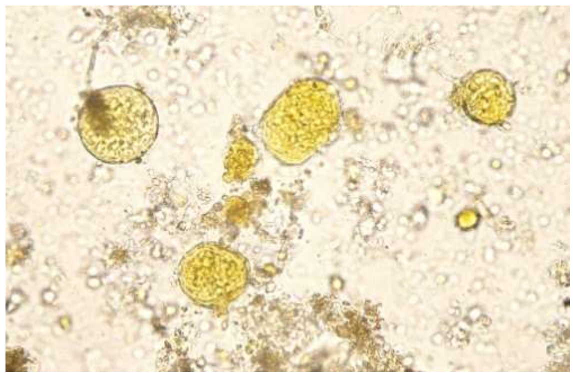
a. Gray-white, Gray-black



b. Gray-white, Gray-brown, Black-brown, White

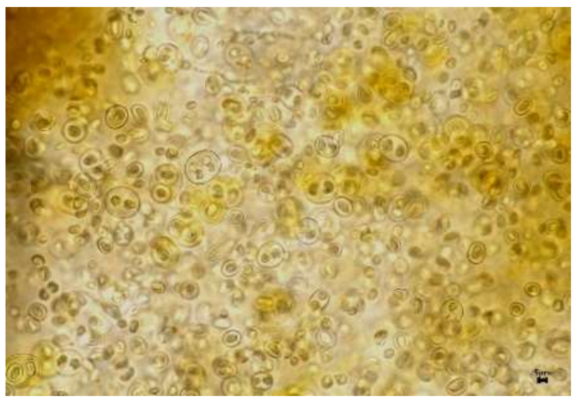


c. *Scytonema bohneri*



d. *Gomphosphaeria* sp.

e. *Gloeocapsa rupicola*



f. *Gloeothece rupestris*

Fig. 5. Micrographs of biological communities and some species on the east-facing marble surface of Hall of Prayer for Good Crops in Temple of Heaven Park, Beijing, China.

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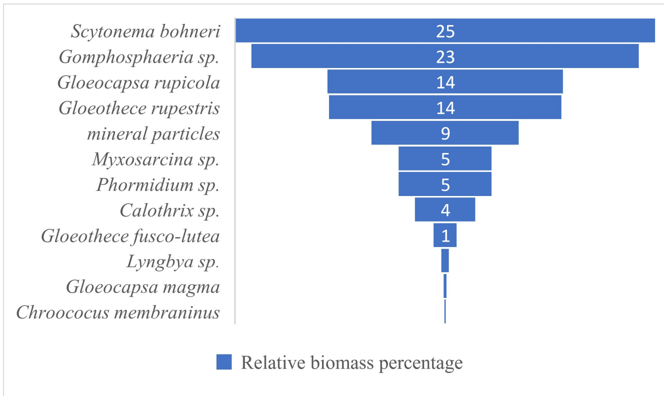

Fig. 6. Biological population relative biomass percentage on the east-facing marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

3.2.2 Characteristics of Biological Populations on West-facing Rock Surfaces

The biological communities on west-facing rock surfaces are primarily characterized by black hairy, black membranous, yellow-green leathery, gray-black leathery, yellow-green, brown, and gray-green appearances. The main species include *Scytonema millei*, mosses, *Schizothrix fasciculata*, *Myxosarcina* sp., *Asterocapsa atrata*, *Gloeocapsa crepidinum*, *Gomphosphaeria* sp., and *Gloeocapsa rupicola* et al（Fig. 7）. Among these, the dominant species are *Scytonema millei* and mosses et al, accounting for 28% and 20% of the relative biomass percentage respectively（Fig. 8）.

a. Gray-black leathery　　b. Black hairy and membranous

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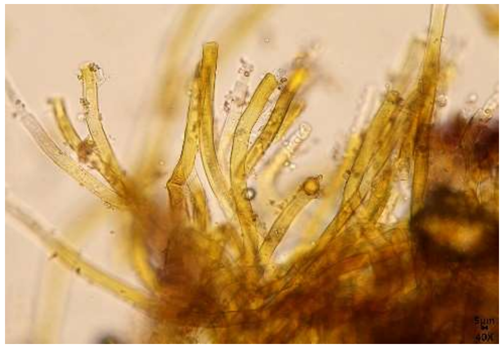
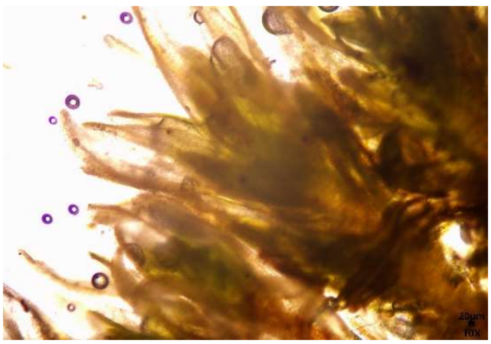


c. Yellow-green, Gray-green, Brown

d. *Scytonema millei*



e. moss

f. *Schizothrix fasciculata*

Fig. 7. Micrographs of biomes and some species on the west-facing marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

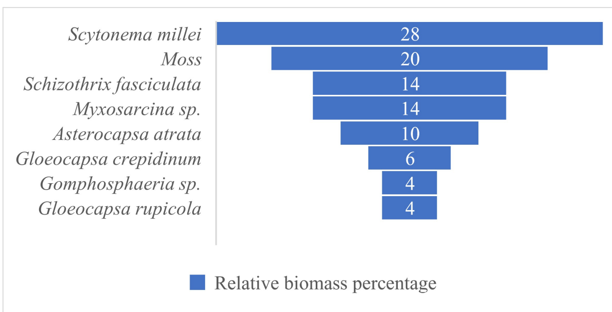


Fig. 8. Biological population relative biomass percentage on the west facing marble surface of Temple of Heaven Park, Beijing, China.

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3.2.3 Characteristics of Population Distribution on North-facing Surfaces

The biological communities on north-facing rock surfaces are primarily characterized by gray-brown membranous, brown, gray-black, yellow-green, black-brown, gray-white, brown crusty, brown carpet-like, brown-black leathery, and brown-black membranous appearances. The main species include *Myxosarcina* sp., *Gomphosphaeria* sp., *Gloeocapsa crepidinum*, *Schizothrix fasciculata*, *Asterocapsa atrata*, *Scytonema millei*, *Calothrix* sp., mosses, *Gloeocapsa rupicola*, *Microcoleus* sp., *Chroococcus* sp., *Gloeothece rupestris*, *Lyngbya* sp., *Gloeocapsa* sp., *Scytonema bohneri*, and *Synechocystis* sp. et al（Fig. 9）. Among these, the dominant species are *Myxosarcina* sp. and *Gomphosphaeria* sp., accounting for 17% and 15% of the relative biomass percentage respectively（Fig. 10）.

a. Gray-brown membranous

b. Gray-black

c. Yellow-green

d. Gray-white

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e. *Calothrix* sp. f. *Microcoleus* sp.

Fig. 9. Micrograph of biological communities and some species on the north facing marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

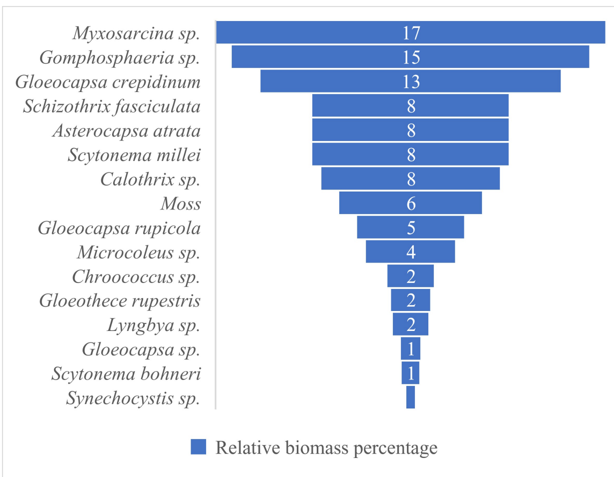

Fig. 10. Relative biomass percentage of biological population on the north facing marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing，China.

3.2.4 Characteristics of Population Distribution on South-facing Surfaces

The biological communities on south-facing rock surfaces are primarily characterized by gray-green leathery, gray-white, gray-black membranous, black leathery, gray-black, brown-yellow, and green powdery layer appearances. The main species include *Scytonema millei*, *Nostoc calcicola*, *Asterocapsa atrata*, *Myxosarcina* sp., *Phormidium* sp., *Gloeocapsa crepidinum*, *Chroococcus membraninus*, *Schizothrix*

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delicatissima, *Schizothrix* sp, *Microcoleus* sp., *Aphanocapsa muscicola*, *Chroococcus lithophilus*, *Lyngbya* sp., *Gloeocapsa* sp., and *Gloeocapsa sanguinea* et al（Fig. 11）. Among these, the dominant species are *Scytonema millei* and *Nostoc calcicola*, accounting for 25% and 20% of the relative biomass percentage respectively（Fig. 12）.

a. Some carved decorations have been completely destroyed

b. Gray-white, Gray-black

c. Black leathery

d. Green powdery layer

Fig. 11. Field photo of biomes on the south facing marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

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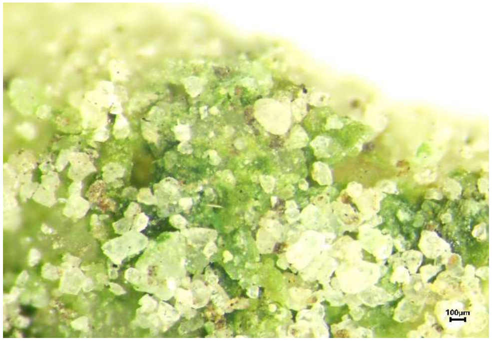
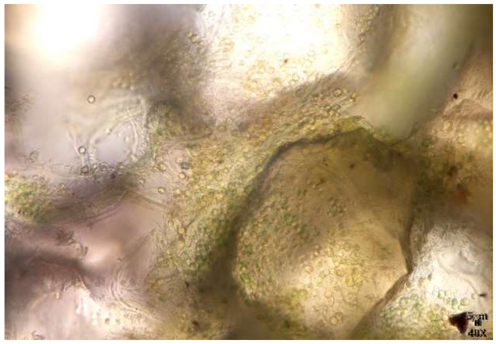
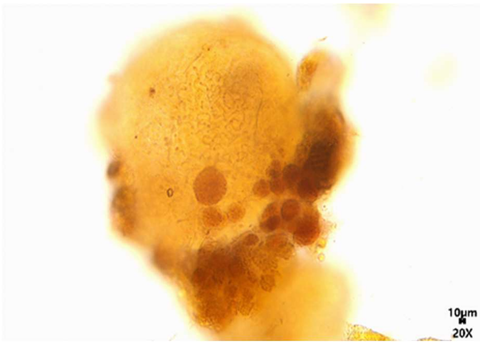


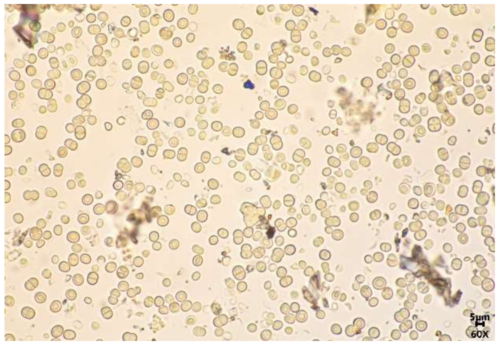
a. Green powdery layer magnified 60x



b. Green powdery layer magnified 400x

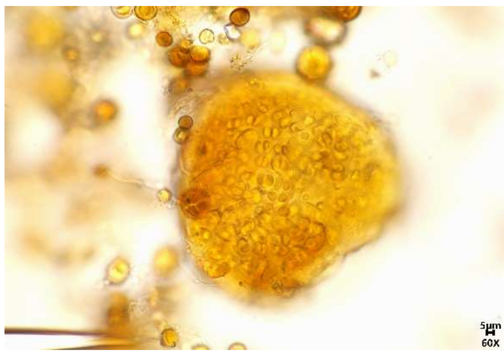


c. *Nostoc calcicole*



d. *Chroococus membraninus*

e. *Schizothrix delicatissima*



f. *Chroococcus lithophilus*

Fig. 12. Micrograph of biomes and some species on the south facing marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

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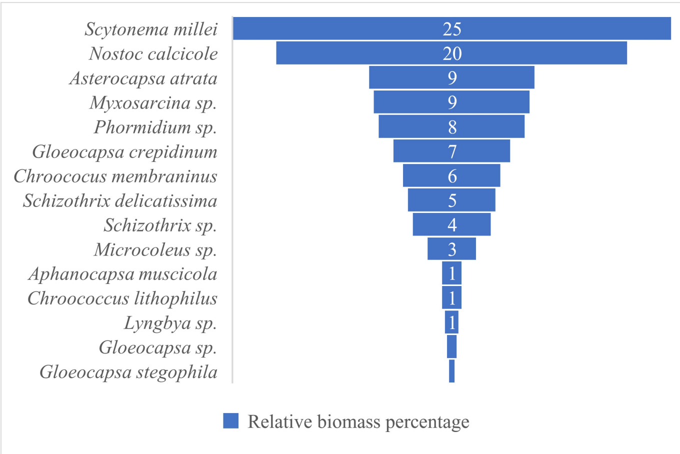

Fig. 13. Biological population relative biomass percentage on the south facing marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

3.2.5 Comparison of Populations on Different Orientations

The main aerophytes algae on rock surfaces include spherical algae, small filamentous algae, and large filamentous algae. Their distribution is primarily influenced by the substrate's looseness, sunlight, and moisture. From spherical algae to small filamentous algae to large filamentous algae, they require increasingly loose substrates, more moisture, and longer sunlight exposure (Table 1). Mosses generally prefer shaded and moist environments.

Although the east and west sides of the Hall of Prayer for Good Harvests in the Temple of Heaven Park receive sunlight for half a day each (Table 2), the eastern side receives sunlight in the morning when the rock surface temperature is lower. Even with abundant sunlight, the algal growth on the eastern surface is not as good as on the western side. The western side receives sunlight in the afternoon when the rock surface temperature is higher, providing both water and heat conditions simultaneously, which is more conducive to algal growth. This results in the appearance of *Scytonema millei*, the algae that prefers to grow on looser substrates, as well as more moss plants, leading to more severe weathering on the western rock surface. The north-facing side is shaded, with slower water evaporation, mainly supporting the growth of spherical algae, and experiencing relatively weaker weathering. The south-facing side receives longer sunlight exposure and weathers faster, with the carved patterns on the rock surface completely destroyed (Fig. 11a). The substrate has a high degree of looseness, even allowing for the appearance of large filamentous algae like *Nostoc*. *Nostoc* typically prefers to live in soil rather

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than on rock surfaces, indicating that the south-facing marble has weathered very severely, forming a loose, thick weathered layer similar to soil. However, mosses are not present on the south-facing side. This may be due to the long sunlight exposure on the south-facing side, which leads to rapid evaporation, causing the rock surface to become excessively dry.

The sensitivity of aerophytic algae to microenvironments is well revealed through the analysis of the composition of aerophytes populations on marble surfaces with different orientations of the Hall of Prayer for Good Harvests.

Table 1

Requirements of aerophyte growth on rock surface environment.

Epilithic Aerophytes	Rock Surface Substrate Looseness	Rock Surface Moisture	Rock Surface Sunlight Duration
Spherical algae	compact	dry	less
Small filamentous algae			
Large filamentous algae	loose	wet	more
Mosses	Relatively loose, shaded and moist environment		

Table 2

Environmental characteristics and dominant species of marble surface of Hall of Prayer for Good Harvest in Temple of Heaven Park, Beijing, China.

Marble Surface Orientation	Sunlight	Moisture	Environmental Characteristics	Dominant Species
North-facing	None	Slow evaporation	Cold and humid	Spherical algae
East-facing	Half day	Rapid evaporation in the morning	Warm and humid	Small filamentous algae, Spherical algae
West-facing	Half day	Rapid evaporation in the afternoon	Hot and humid	Small filamentous algae, Mosses
South-facing	Full day	Rapid evaporation during the day	Hot and dry	Small filamentous algae, Large filamentous algae

3.3 Relative Biomass of Different Colored Biological Communities on Rock Surfaces in the Study Area

The colors displayed by aerophytic algae and mosses on rock surfaces differ from those observed under a microscope. In this paper, the former is referred to as the "visual color," while the latter is called the "microscopic color." The visual color is the community color presented when different populations aggregate together, whereas the microscopic color is the color of different species observed under magnification through a microscope. Often, communities of algae with different microscopic colors appear mostly black or gray-black of visual color.

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The visual colors of biological communities on rock surfaces in the study area can be categorized into gray-black, gray-white, black, brown, black-brown, gray-brown, yellow-green, gray-green, white, green, and brown-yellow. Their relative biomass is shown（Fig. 14）. The most common color is gray-black, followed by gray-white, black, brown, and black-brown. These are also typical colors exhibited by aerophytic cyanobacteria in the field, sometimes referred to as "ink bands." For example, the Nine Horses Fresco Hill (Jiuma Huashan) in the Guilin landscape of China is formed due to aerophytic cyanobacteria growing on the rocks, creating black ink-like bands.

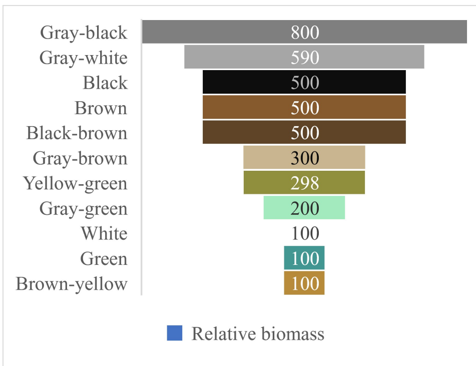


Fig. 14. Relative biomass of biomes with different colors on the marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

3.4 Relative Biomass of Population Composition in Different Colored Biological Communities on Rock Surfaces in the Study Area

The relative biomass of population compositions in different visually colored biological communities on rock surfaces in the study area is shown（Fig. 14）. An analysis of the main population compositions of these biological communities is presented （Fig. 15）. The colors of biological communities on rock surfaces in the study area are primarily composed of black, brown, gray, green, and yellow, as well as combinations of these colors (gray-black, gray-white, black-brown, gray-brown, yellow-green, gray-green, and brown-yellow). The correlation between color combinations and population composition is not very apparent, which also indicates that determining microscopic color (population composition) through visual color is a complex and difficult task. Nevertheless, some patterns can be observed:

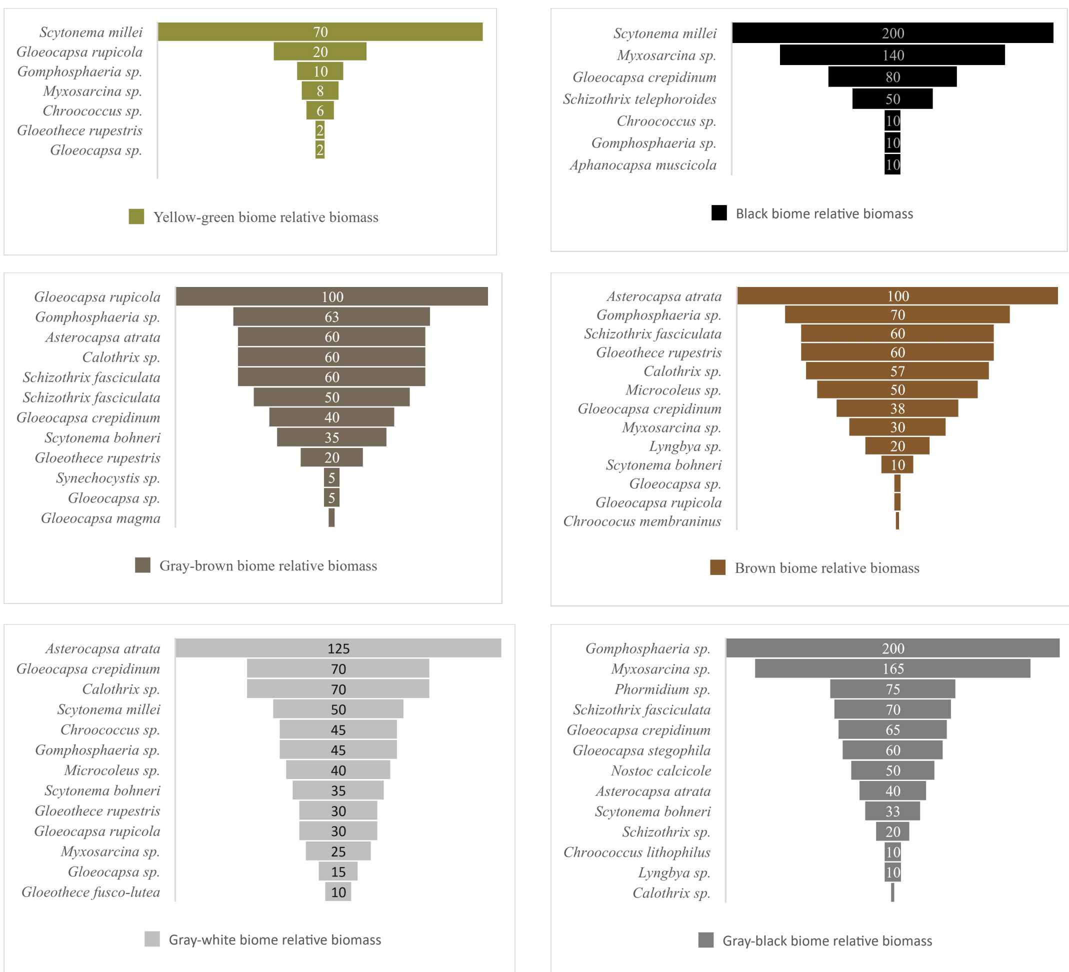
1. Species like *Scytonema millei*, *Myxosarcina* sp., *Asterocapsa atrata*, *Gomphosphaeria* sp., and *Gloeocapsa rupicola* tend to make the community color darker, presenting as black, brown, gray, or combinations of these.

2. The white-colored areas observed visually are mineral particles, not biological, when viewed under a microscope.

3. The visually green-colored areas (mainly referring to the unique blue-green color of cyanobacteria) are mineral particles and *Chroococcus membraninus*.

4. The yellow-green visual color is mainly composed of mosses.

5. The brown-yellow visual color is primarily composed of *Nostoc calcicole* etc.



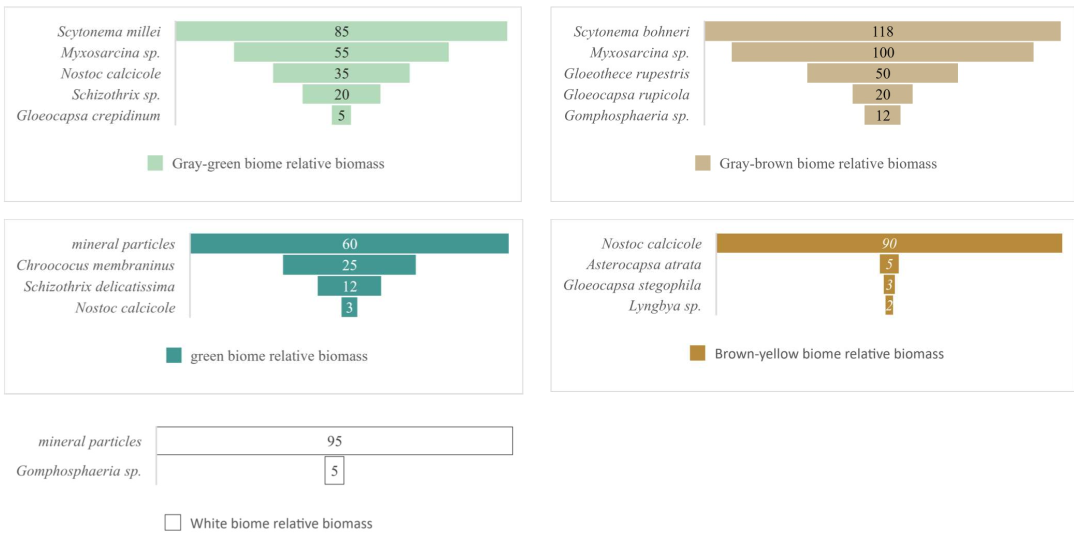


Fig. 15. Relative biomass of community composition of different colors on marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

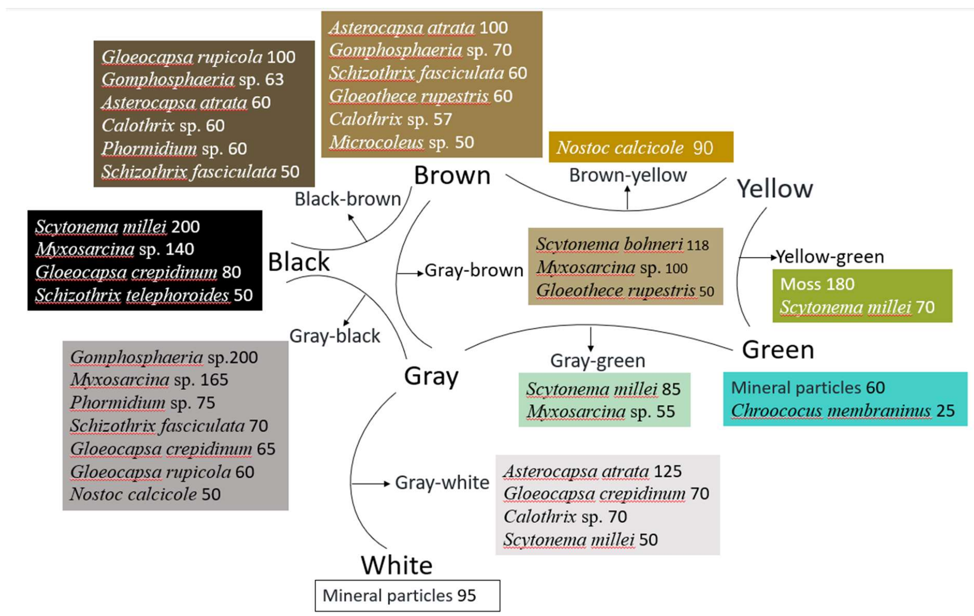


Fig. 16. Analysis of main population composition of different color biomes on marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

3.5 Relative Biomass of Population Composition in Different Morphological Biological Communities on Rock Surfaces in the Study Area

The biological communities on rock surfaces in the study area exhibit different morphologies, including membranous, hairy, carpet-like, leathery, shell-like, and powdery layers. Their relative biomass of population composition is shown （Fig. 17）. A diagrammatic explanation of the formation of these community morphologies is presented （Fig. 18）.

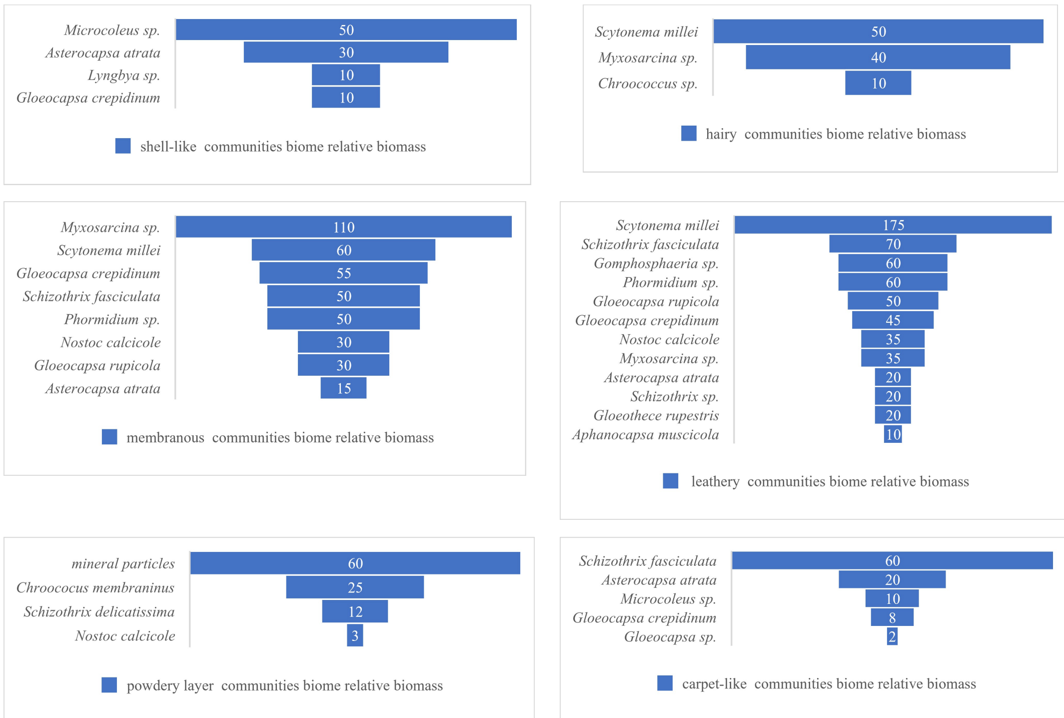


Fig. 17. Relative biomass of different forms of community on marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

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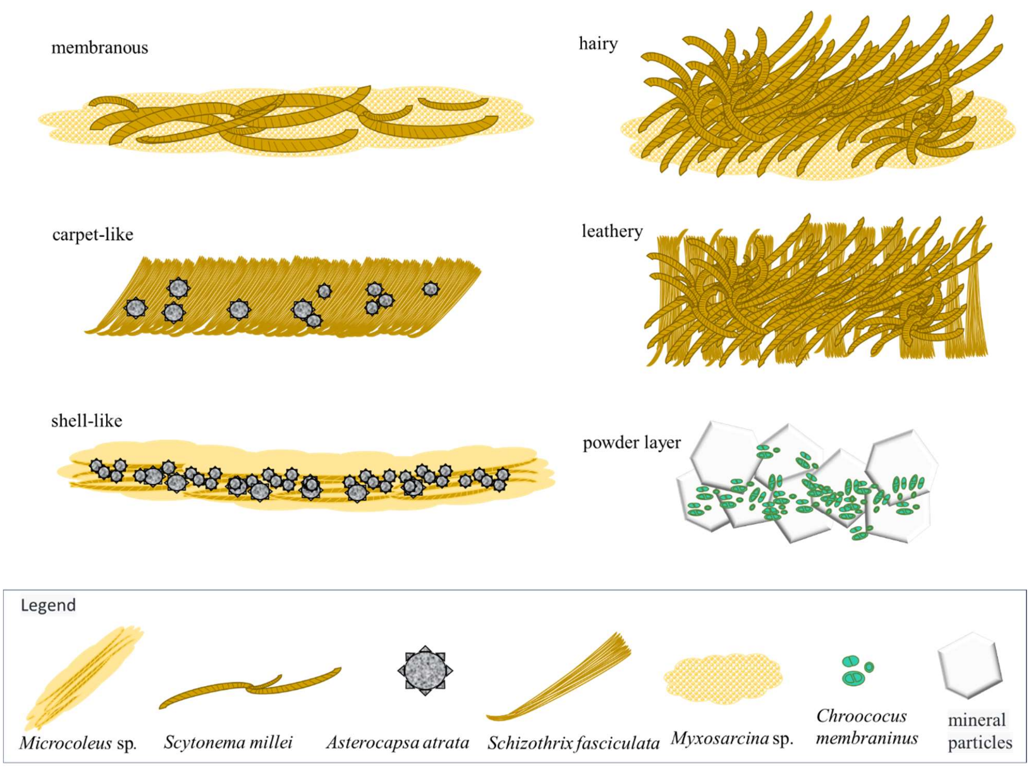

Fig. 18. Morphological genesis diagram of different communities on marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

The dominant species in the membranous biological communities are mainly *Myxosarcina* sp. and *Scytonema millei*. The former accounts for a relative biomass of 110, while the latter accounts for 60（Fig. 17）. *Myxosarcina* sp. is a spherical alga（Fig. 4a）. It has thick individual sheaths, forming a dense colonial mucilage. *Scytonema millei* grows interspersed within, forming a membrane-like community（Fig.18）. When the relative biomass of *Scytonema millei* in the community exceeds that of *Myxosarcina* sp., it forms a hairy community（Fig. 18）. The dominant species in the carpet-like communities are mainly *Schizothrix fasciculata* and *Asterocapsa atrata*. The former accounts for a relative biomass of 60, while the latter accounts for 20（Fig. 17）. *Schizothrix fasciculata* grows densely together, forming a carpet-like structure（Figure 18）. The dominant species in the leathery biological communities are mainly *Scytonema millei* and *Schizothrix fasciculata*. The former accounts for a relative biomass of 175, while the latter accounts for 70（Fig. 17）. *Scytonema millei* intertwines, with *Schizothrix fasciculata* interspersed within（Fig. 18）. The dominant species in the shell-like

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biological communities are mainly *Microcoleus* sp. and *Asterocapsa atrata*. The former accounts for a relative biomass of 50, while the latter accounts for 30（Fig. 17）. *Microcoleus* sp. has well-developed sheaths, with multiple algal filaments inside each sheath. The sheaths of multiple *Microcoleus* sp. aggregate to form a mucilaginous layer, with *Asterocapsa atrata* dispersed within. When the mucilaginous layer dries, it cracks into numerous small pieces. The edges of each piece detach from the rock surface and curl up, forming a shell-like structure（Fig. 18 and Fig. 19）. The powder layer is a severely weathered surface（Fig. 11d）. Under microscopic observation, it mainly consists of mineral particles and *Chroococus membraninus*, with the former accounting for 60 and the latter for 20 of the relative quantity（Fig. 17）. *Chroococus membraninus* is distributed on the surface and in the crevices of mineral particles（Fig. 12a and b）. The color of the community appears as a mixture of the green color of *Chroococus membraninus* (or the blue-green color characteristic of cyanobacteria) and the white color of mineral particles.

3.6 Biological Weathering on Rock Surfaces in the Study Area

The growth distribution of aerophytes on rock surfaces in the study area is closely related to the surface smoothness and texture of marble (Table 3). If the marble surface is uneven or has a non-uniform texture, the aerophytes communities will be distributed in a spotted pattern (Fig. 19a). Dissolution forms solution pits and cavities (Fig. 19b), which further expand into solution basins (Fig. 19c, d). If the marble surface has linear textures or non-uniform texture with joint stripes, the aerophytes communities will be distributed in a linear pattern (Fig. 19e). Dissolution forms solution marks and grooves (Fig.19f), which further expand into solution channels (Fig. 19g). If the marble surface is smooth and has a uniform texture, the aerophytes communities will be distributed in a planar pattern (Fig. 19h). Dissolution forms a weathering layer or exfoliation layer (Fig. 19i). Some studies also suggest that the type of stone, its position on the building, and the surface roughness of the stone greatly influence biological growth (Korkanç and Savran, 2015).

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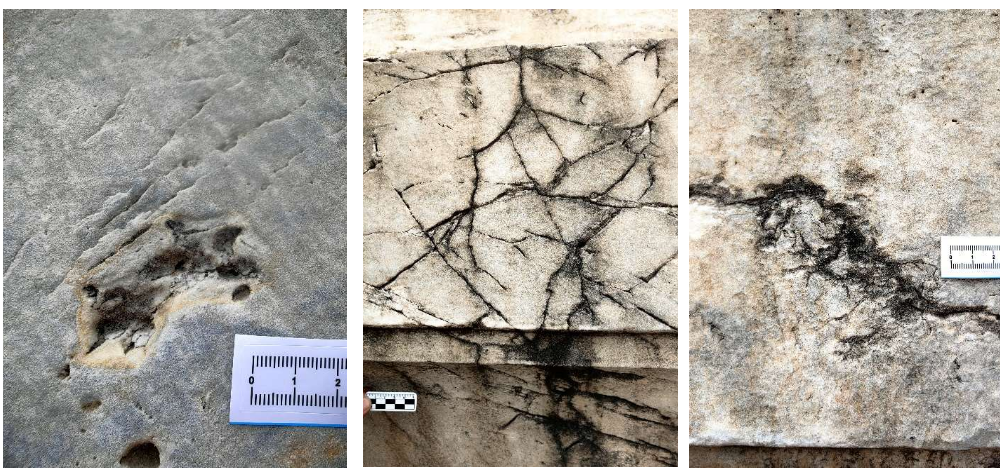
Table 3

Characteristics of marble in Temple of Heaven Park, Beijing, China. and the process of biological corrosion on its surface.

Marble Characteristics	Biological Community Distribution	Resulting Dissolution Forms	Development Process
Uneven surface or non-uniform texture	Spotted distribution	Solution pits, cavities, and basins	
Surface with linear textures or non-uniform texture with joint stripes	Linear distribution	Solution marks, grooves, and channels	
Smooth surface with uniform texture	Areal distribution	Weathering layer, exfoliation layer	

a. Biocommunity point distribution b. Solution pores and solution cavities c. Sinkhole



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d. Solution pit   e. Biocommunity linear distribution   f. Solution marks and solution grooves

g. Solution channel   h. Biocommunity areal distribution   i. Exfoliation layer

Fig. 19. Biological weathering forms on the marble surface of Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

The spotted distribution of biological communities gradually expands into linear distribution, and then into planar distribution. Solution pits, basins, and cavities also further enlarge their dissolution forms, developing into solution marks, grooves, and channels. For example, in the weathering process of the cloud-patterned white marble water spouts on the Hall of Prayer for Good Harvests in the study area, biological communities first accumulate and grow in the depressions of the patterns (Fig. 20a, b). These areas retain more moisture, so they are the first to undergo biological weathering, forming deeper solution cavities and channels. The communities then gradually spread to the surrounding areas, developing into linear distributions, and then areal distributions, leading to flaking of the rock surface (Fig. 20c). This partially destroys the pattern structure, further expanding the area and depth of dissolution, forming a loose powder layer (Fig. 11a, d, Fig. 12a, b, Fig. 20d, e, f).

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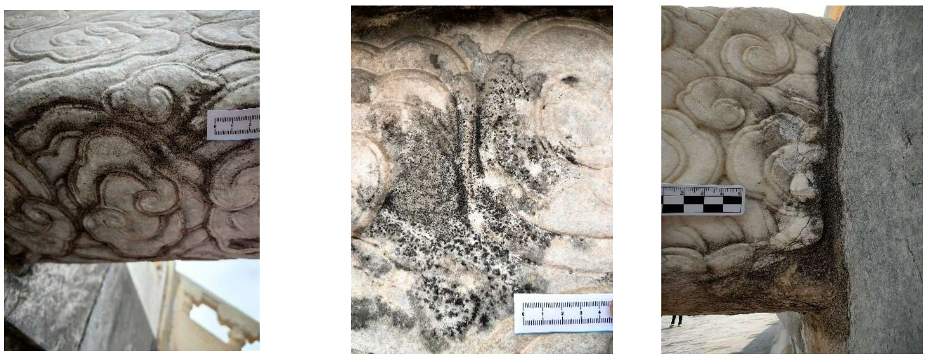

a. Organisms gather and grow in the depressions of the patterns

b. Organisms gather and grow in the depressions of the patterns

c. Flaky exfoliation on the surface of the emerging cloud-like decorations

d. Some emerging cloud-like decorations are structurally damaged

e. Emerging cloud-like decorations have weathered almost completely

f. Emerging cloud-like decorations form a loose powdery layer

Fig. 20. Biological weathering process of the emerging cloud-like marble decorations on the Hall of Prayer for Good Harvests in Temple of Heaven Park, Beijing, China.

The dissolution mechanism of aerophytes communities on rocks in the study area primarily involves the organisms' attempt to obtain inorganic nutrients such as calcium and magnesium ions from the rock. These aerophytes communities can secrete organic acids, which release calcium and magnesium ions from the rock, thereby obtaining inorganic nutrients for their growth and development. Through this acid erosion process, aerophytes communities can "eat away" at the rock, forming tiny hemispherical dissolution pits (Fig. 21), thus damaging the surface structure of the rock and forming an underlying weathering layer (Tian et al., 2004).

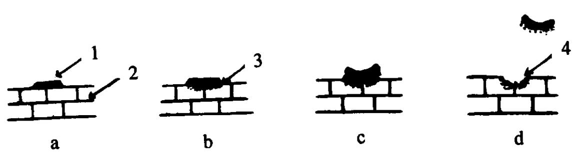

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Fig. 21. Schematic diagram of the formation of hemispherical small-scale dissolution forms in Yunnan Stone Forest, China. 1.Cyanobacterial crust; 2.Carbonate rock; 3.Underlying weathering layer; 4. Hemispherical dissolution morphology. a. Shell-like, membrane-like and other cyanobacterial communities attach to the surface of carbonate rocks; b. The cyanobacterial communities exert long-term biodissolution effects on the underlying rock, forming an underlying weathering layer; c. During dry climate conditions, the algal crust contracts, and the edges of the crust gradually detach from the rock surface; d. As the algal crust further dries and shrinks, under external forces (such as wind), it completely detaches from the rock surface. Due to the adhesive nature of the algal crust, the detached crust carries away some of the white powder from the underlying weathering layer, leaving behind a hemispherical dissolution morphology at that location. (Tian et al., 2004)

4 Discussion

This study primarily focuses on algae and mosses visible under biological microscopes and does not address other bacteria. Whether other bacteria are present is a matter that requires further verification and in-depth research in the future.

Detailed investigation and research on biological communities on marble surfaces help reveal the mechanisms and processes of biological weathering of marble artifacts. This can lead to more targeted scientific methods for protecting marble cultural relics. The weathering of marble cultural relics in the Temple of Heaven Park is due to physical, chemical, and biological factors. However, in many cases, biological factors are the most destructive protagonists. They often form biofilms on marble surfaces, corroding stone cultural relics over large areas, continuously damaging rocks through biophysical and biochemical means.

Connections and issues between different research levels, methods, and results in this paper. This paper studies the aerophytes on rock surfaces in the research area in terms of biological community population composition, community color and morphology, and community distribution characteristics (Table 4). The spotted, linear, and planar distributions of biological communities on rock surfaces in the study area are composed of many microcommunities. These microcommunities exhibit different morphologies, including membranous, hairy, carpet-like, leathery, shell-like, and powder layers. Spotted, linear, and areal distributions of biological communities may be composed of one type of microcommunity or multiple types. Microcommunities are further composed of multiple populations,

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and a population consists of multiple individual organisms of the same species. Community distribution characteristics are observed with the naked eye, without magnification. Community color and shape are observed through stereomicroscopes and the naked eye, magnifying objects 8-56 times (or no magnification if observed with the naked eye). Biological community population composition is identified through biological microscope observation, magnifying objects 40-1000 times. This represents three stages of research with increasing magnification of the research object: 1) Distribution area; 2) Community; 3) Population. Research at each stage is relatively easy to conduct, but the connections between stages are challenging and represent a weakness in this paper. For example, to accurately correlate different colored and shaped communities with their precise population compositions (i.e., connecting the community stage with the population stage) requires statistical analysis of numerous specimens to improve accuracy. For instance, the observation of communities in outdoor settings, specifically the transition between distribution stages and community stages, primarily relies on the naked eye. Only a small number of observations are performed using stereomicroscopes, as detailed stereomicroscopic observations requiring photographs must be conducted indoors. The sampling of cultural relics in scenic areas is extremely limited and must be carried out without damaging the relics. To address this issue, one approach is to enhance the performance of observation equipment to allow for in situ biological community observations outdoors without sampling, or to perform minimal sampling without damaging the relics.

Table 4

Analysis of the stages in biological weathering research on aerophytes on marble in the temple of heaven park, Beijing, China.

Research Level	Distribution Area	Community	Population
Observation Method	Naked eye	Stereomicroscope, naked eye	Biological microscope
Magnification	0	8-56, 0	40-1000
Classification	3 distribution characteristics (point, linear, and areal distribution)	11 colors： gray-black, gray-white, black, brown, black-brown, gray-brown, yellow-green, gray-green, white, green, brown-yellow 6 morphologies： membranous, hairy, carpet-like, leathery, shell-like, and powder layer	30 genera and species： *Myxosarcina* sp.， *Gomphosphaeria* sp.， *Asterocapsa atrata* and so on （Fig.3）
Composition	Composed of multiple communities	Composed of multiple populations	Composed of multiple individuals of a single species

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5 Conclusion

The most dominant species on marble surfaces in the study area is *Myxosarcina* sp., followed by *Gomphosphaeria* sp., *Asterocapsa atrata*, *Gloeocapsa crepidinum*, and *Scytonema millei*. These aerobic algae prefer calcareous environments, are drought-tolerant, slow-growing, and extremely resilient. The biological population composition on marble surfaces facing different directions at the Hall of Prayer for Good Harvests in the Temple of Heaven Park varies due to differences in sunlight exposure. The east-facing side, warm and humid, mainly hosts small filamentous and spherical algae such as *Scytonema millei* and *Gomphosphaeria* sp. The west-facing side, hot and humid, primarily features *Scytonema millei* and mosses, with *Scytonema millei* being a small filamentous alga. The north-facing side, cold and humid, mainly supports spherical algae like *Myxosarcina* sp. and *Gomphosphaeria* sp. The south-facing side, hot and dry, primarily hosts small or large filamentous algae such as *Scytonema millei* and *Nostoc calcicole*. Rock surface biological communities in the study area display various colors, with gray-black being the most common, followed by gray-white, black, brown, and brown-black. Gray-black communities are mainly composed of *Myxosarcina* sp. and *Gomphosphaeria* sp. Rock surface biological communities in the study area exhibit different morphologies, including membranous, hairy, carpet-like, leathery, shell-like, and powder layers. Different morphologies correspond to different population compositions. The growth and distribution of aerophytes on rock surfaces in the study area are closely related to the smoothness and texture of the marble surface. Where the marble surface is uneven or has inconsistent texture, aerophytes communities show a spotted distribution, forming dissolution holes, cavities, and pits. Where the marble surface has linear patterns or uneven texture with joint stripes, aerophytes communities display a linear distribution, forming dissolution marks, grooves, and channels. Where the marble surface is smooth with uniform texture, aerophytes communities exhibit an areal distribution, forming weathering or exfoliation layers. The mechanism of biological dissolution involves aerophytes secreting organic acids, which dissolve inorganic salts from the rock to obtain nutrients, thereby "eating away" at the rock, damaging its surface structure, and gradually weathering the rock. Aerophytes grow abundantly on marble surfaces. Finding ways to prevent or reduce the growth of these organisms is key to slowing down the weathering process of stone cultural relics in the Temple of Heaven Park.

Author contributions

YT completed all the work on the paper, including sampling, photography, experimental data analysis, charting, drawing, and writing the paper, among other tasks.

Competing interests

The author has declared that there are no competing interests.

Acknowledgement

This study was supported by National Science Foundation of China (Grant No. 40872197) and the Development Fund of China University of Geosciences (Beijing) (Grant No. F02114).

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