

Mechanism of Mold-Induced Degradation of Silicone Rubber Under Microgravity in Space Environment

Yao Tan

University of Science and Technology Beijing

Yiding Zhou

Beijing Institute of Spacecraft System Engineering

Chao Cheng

Beijing Institute of Spacecraft System Engineering

Nana Chen

University of Science and Technology Beijing

Xiaowen Song

University of Science and Technology Beijing

Tong Tong

Shenzhou Space Biotechnology Group

Lin Lu

University of Science and Technology Beijing

Shuyuan Zhang

University of Science and Technology Beijing

Wende Zhang

Shenzhou Space Biotechnology Group

Kui Xiao

xiaokui@ustb.edu.cn

University of Science and Technology Beijing

Article

Keywords: Aspergillus niger, real microgravity environment, Silicone Rubber

Posted Date: October 6th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11120932/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Mechanism of Mold-Induced Degradation of Silicone Rubber Under Microgravity in Space Environment

Tan Yao^a, Zhou Yiding^c, Cheng Chao^c, Chen Nana^a, Song Xiaowen^a, Tong Tong^b, Lu Lin^a,

Zhang Shuyuan^a, Zhang Wende^{b,*}, Xiao Kui^{a,*}

^a Institute for Advanced Materials and Technology, University of Science and Technology

Beijing, Beijing 100083, China

^b Shenzhou Space Biotechnology Group, Beijing 100090, China

^c Beijing Institute of Spacecraft System Engineering, Beijing, 100094, China

* Corresponding author.

Xiao Kui, xiaokui@ustb.edu.cn

Zhang Wende, zhangwende2008@sina.com

Abstract: As a key sealing material in the life support and environmental control system of manned spacecraft, the failure mechanism of silicone rubber under mold action and corresponding protection strategies are becoming a research hotspot in space materials. This study, based on the China Space Station's "Microorganism-Material Interaction Scientific Experiment Device" (ISED) platform, conducted in-orbit experiments on the degradation behavior of silicone rubber by *Aspergillus brasiliensis* in a real microgravity environment. Combined with synchronous ground control experiments, techniques such as LC-MS, multi-scale morphology characterization, fluorescence staining analysis, and microscopic infrared spectroscopy were used to systematically analyze the metabolic characteristics of *Aspergillus brasiliensis*, material corrosion morphology, and chemical structure changes in both space and ground environments. The results showed that the total amount of organic acids secreted by *Aspergillus brasiliensis* in the ground environment was significantly higher than that in the space environment. Only spores were found on the surface of all samples, with a higher degree of spore accumulation on the surface of ground group samples, while spores were sparsely distributed on the surface of space group samples, consistent with the stronger biological activity observed in fluorescence staining analysis of the ground group. Semi-quantitative analysis by microscopic infrared spectroscopy indicated that the biodegradation primarily targeted C=C functional groups, and the degree of material degradation in the ground environment was higher than that in the space group. This study elaborates in detail the influence mechanism of microgravity on mold/interface interaction and silicone rubber degradation behavior, providing important scientific basis for spacecraft material protection design and on-orbit service reliability.

Key Words: *Aspergillus niger*; real microgravity environment; Silicone Rubber

1 Introduction

Silicone rubber, due to its excellent high and low temperature resistance, high

elasticity, electrical insulation, and adaptability to the space environment, is a core polymer material in the life support and environmental control systems, sealing components, and electronic insulation components of space stations ^[1,2]. Among them, silicone rubber, with its stable mechanical properties, excellent high and low temperature resistance, and outstanding sealing performance, has become a key material for aerospace sealing and structural support ^[3]. Manned spaceflight, as a core strategic field for expanding human living space and developing space resources, relies on the long-term stable operation of space stations in orbit as a key premise for the sustainable development of aerospace ^[4]. In space stations, microorganisms (especially fungi) can easily colonize and proliferate through astronaut metabolism, equipment carriage, and other pathways ^[5,6]. During the synthesis and processing of silicone rubber materials, organic additives such as vulcanizing agents and plasticizers are easily retained, providing carbon, nitrogen, and other nutrient substrates for mold growth ^[7,8]; coupled with the relatively closed cabin conditions in the space station, controllable humidity (about 40%-60%), and temperature maintained at 20-30°C, which coincidentally match the optimal growth conditions for mold ^[9,10], the risk of microbial corrosion of silicone rubber is significantly increased.

In recent years, research on the failure and degradation behavior of silicone rubber has mainly focused on thermo-oxygen aging and multi-field coupled aging. Cao Jinnan et al. ^[11] systematically investigated the degradation behavior of sulfide phenyl silicone rubber at temperatures (180°C, 210°C), finding that at low temperatures (180°C), side chain oxidation predominates, main chain breakage is mild, and performance degradation is smooth. At high temperatures (210°C), main chain breakage becomes dominant, causing extensive Si-O bond breakdown, shortening molecular chains, crosslinking structure breakdown, and a sharp decline in performance. Wang Zheng et al. ^[12] used UVA and UVB light sources to accelerate the aging of silicone rubber, confirming that UVB severely damages the molecular chains of silicone rubber, causing massive cleavage of Si-C bonds and side group methyl groups, generating more low-molecular-weight cyclic siloxanes and hydrocarbon cracking products, with more severe degradation; UVA mainly induces

slow oxidation reactions and mild side chain decomposition, releases fewer small molecule products, and results in a relatively mild rate of material degradation. Zhang Xueqin et al.^[13] took high-temperature vulcanized silicone rubber as their research object, focusing on the dual factors of heat and moisture to characterize material structural degradation. They found that water molecules induce the hydrolysis of the Si-O main chain, while high temperatures accelerate free radical oxidation and accelerated the oxidative decomposition of side-chain methyl groups. This aligns with the degradation patterns of silicone rubber in simulated tropical marine atmospheres by Wang Ruiyuan et al.^[14]. Gu Yu^[15] and others analyzed the phenomenon of a sudden drop in hydrophobicity of silicone rubber and found that after immersion, an oily attachment layer containing bacteria, fungi, and their secretions forms on the surface, indicating that silicone rubber materials are easily covered by microorganisms and thus affect equipment safety. Wallström S^[16] and others conducted a qualitative analysis of the community structure of biofilms on the surface of naturally serviced silicone rubber, clarifying that mold is the key microorganism responsible for surface erosion. Lugauskas A et al.^[17] found that although organosilicon polymers have high chemical stability, under long-term humid and eutrophic conditions, molds can still attack side chain alkyl groups and Si-O bonds, causing material structural degradation. Yang Shifang et al.^[18] used Lewis acid to pretreat silicone rubber, then incorporated *Aspergillus brasilius* for static culture. They found that after acid pretreatment, *Aspergillus brasilius*'s ability to metabolize and secrete organic acids, hydrolases, and other metabolites was enhanced, further accelerating chemical bond breakage and material oxidative aging. Currently, research on the interaction between fungi and silicone rubber under real microgravity environments remains incomplete. This research gap also limits our understanding of the mechanisms by which microorganisms corrode and degrade silicone rubber materials under real space service conditions, and there is an urgent need for systematic validation combined with space-specific environmental factors.

Therefore, this paper takes silicone rubber as the research object and carries out on-orbit exposure experiments to study the corrosion behavior of *Aspergillus niger* on

it in a real microgravity environment. By simultaneously conducting ground-based control experiments, it reveals, from macro to micro scales, the differences in surface damage morphology and degradation behavior of silicone rubber under different gravity conditions. Using characterization methods such as optical microscopy, laser confocal microscopy, scanning electron microscopy, and micro-infrared spectroscopy, the study focuses on the impact of fungi on the degradation behavior of silicone rubber under microgravity conditions. The research results further improve the theoretical system of microorganism-induced silicone rubber corrosion in real microgravity environments and can provide experimental evidence and theoretical guidance for mold-resistant modification and reliability assessment of aerospace silicone rubber materials.

2 Experimental Materials and Methods

2.1 Experimental Materials

The material used in this study is silicone rubber. Before the experiment, the samples were processed into circular discs with a diameter of 29 mm and a thickness of 1 mm. Two small holes with a diameter of 1.8 mm were symmetrically drilled at the edges of the samples, as shown in Figure 1, to facilitate installation in the culture module of the experimental device. Before the experiment, the material sheets were sterilized by soaking in 75% ethanol for 15 minutes, combined with 15 minutes of ultraviolet irradiation.

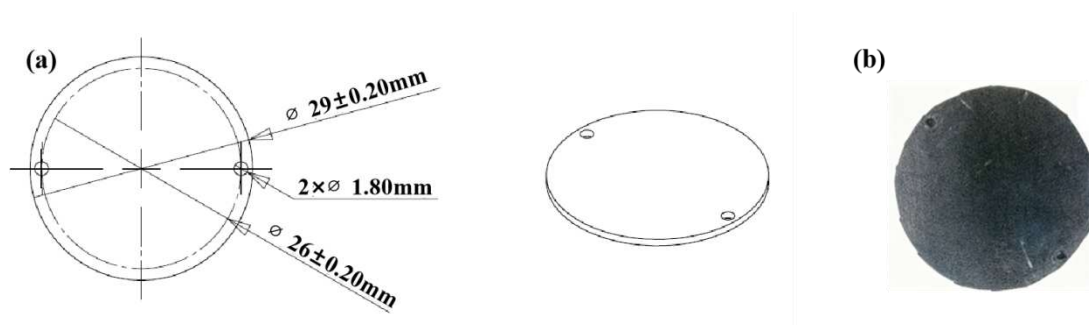


Figure 1 (a) Dimensions specifications of the silicone rubber sample; (b) Silicone rubber sample

2.2 Spore Suspension Preparation and Sample Inoculation

The standard strain *Aspergillus brasiliensis* ATCC® 16404TM was used as the experimental strain, purchased from the Guangdong Institute of Microbiology, China. The strain was long-term preserved by suspending spores in 25% glycerol protective solution and freezing in an ultra-low temperature freezer at -80°C. Before the experiment, the glycerol spore suspension was inoculated on potato dextrose agar (PDA: 3.0 g/L potato infusion powder, 20.0 g/L glucose, 14.0 g/L agar) plates, and the inoculated plates were incubated at 28°C for 10 days for mycelial growth and sporulation. Mature fungal samples were then transferred to fresh PDA plates and incubated for another 10 days under the same conditions until the fungi completely covered the PDA plate surface. Spores were scraped with a sterile inoculation loop and rinsed with sterilized inorganic salt nutrient solution (composition shown in Table 1). The solution was filtered through multiple layers of gauze and counted using a hemocytometer, finally preparing a spore suspension with a concentration of 10^7 cfu/mL for the study.

The sterilized samples were placed in glass Petri dishes, and the spore suspension was evenly sprayed at a height of approximately 20 cm from the samples using a spray bottle, repeated 10 times. After drying the samples on a clean bench, the inoculation step was repeated three times. After inoculation, two samples were randomly selected from each material sheet for elution, and the inoculum on the sample surface was quantified using the plate counting method. The final inoculum per sample was approximately 10^6 spores.

Table 1 Composition of the culture medium

Reagent	g/l
Potassium dihydrogen phosphate(KH_2PO_4)	0.7
Dipotassium hydrogen phosphate(K_2HPO_4)	0.3
Magnesium sulphate($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$)	0.5
Sodium nitrate(NaNO_3)	2.0
Potassium chloride(KCl)	0.5
Ferrous sulphate($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$)	0.01

2.3 Synchronous Space-Ground Corrosion Experiments

The space corrosion test platform used in this study is based on the Interaction System for Extraterrestrial-microbe-materials Dynamics (ISED), provided by China Shenzhou Space Biotechnology Group. The device provides necessary environmental conditions for microbial culture, including temperature control, sterile water injection, and video monitoring, supporting long-term on-orbit microbial corrosion experiments. The structure and sample loading of the test device have been detailed in previous studies^[19,20,21]. After the inoculated samples reached the orbital space station with the experimental module and spacecraft, the ground control center injected ($1.5 \text{ mL} \pm 0.5 \text{ mL}$) sterile water onto the sample surface via remote commands to activate spores, officially launching a 90-day on-orbit experiment. The temperature was maintained at $28 \pm 0.5^\circ\text{C}$ throughout the experiment. After the experiment, astronauts removed the culture module from the test device, sealed it in a special cabin bag, and stored it at 4°C for return. To ensure experimental consistency between space and ground controls, the ground group used a simulation device identical in structure to the space group and conducted synchronous experiments in a controlled environment. After the landing of the Shenzhou-16 manned spacecraft, all samples were extracted and subsequently used for systematic analysis of morphological, compositional, and performance changes.

2.4 Sample Analysis Methods

2.4.1 Fungal Targeted Metabolite Detection

Detection of Mould Targeted Metabolites: An ultra-high performance liquid chromatography-tandem high-resolution Orbitrap mass spectrometer (UHPLC-QE, Thermo, USA) was used for metabolite detection. First, the sample culture chamber was rinsed with sterile water, and the rinsate was filtered through a $0.22 \mu\text{m}$ needle filter. An appropriate amount of filtrate was taken, added with 1 mL methanol / chloroform extract(7:3, v/v), vortexed and mixed, then incubated on ice for 30 min.

Then 0.6 mL ultrapure water was added and mixed, centrifuged at 12000 rpm for 10 min at 4 °C, and the supernatant was collected. The extraction was repeated twice and the supernatants were combined for standby. 40 µL of supernatant was added with 10 µL of 0.1 M 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (EDC) and 10 µL of 0.1 M 3-nitrophenylhydrazine (3-NPH) solution, and derivatized at 40 °C for 30 min. Chromatographic separation was performed on a Waters BEH C18 column (50 mm × 2.1 mm, 1.8 µm). Mobile phase A was ultrapure water (containing 0.1% formic acid), mobile phase B was 100% acetonitrile (containing 0.1% formic acid). The column temperature was 40 °C, flow rate was 0.35 mL/min, and gradient elution was adopted. The gradient elution started with A: B = 90:10 v/v; at 2.0 min, A: B = 90:10 v/v; at 12.0 min, A: B = 10:90 v/v; at 14.0 min, A: B = 10:90 v/v; at 14.1 min, A: B = 90:10 v/v; at 16.0 min, A: B = 90:10 v/v. Samples were placed in a 4 °C autosampler during the entire analysis process, with an injection volume of 2 µL. The mass spectrometer used an electrospray ionization source (ESI) in negative ion mode, ion spray voltage -2.8 kV, sheath gas pressure 40 arb, auxiliary gas pressure 10 arb, ion transfer tube temperature 320 °C, auxiliary gas heater temperature 350 °C, and scanning mode Fullms-ddMS2.

2.4.2 Characterization of Sample Corrosion Morphology

The macroscopic corrosion morphology of the samples was observed at different magnifications using an AO-HD228SD Ostron electron microscope; a stereo microscope (Zeiss, Stemi 305, Germany) and a laser confocal scanning microscope (CLSM, VK-X250 3D, Keyence, Japan) were used to capture the three-dimensional surface profile of the samples; a field emission scanning electron microscope (SEM, Gemini SEM 300, Zeiss, Germany) was used to further observe the microscopic corrosion morphology of the samples. Before SEM observation, Au was sputtered onto the sample surface to improve conductivity.

2.4.3 Fluorescent Staining Analysis

Stain the samples with PI and keep them in the dark for 15 minutes. PI binds to the DNA of inactivated biofilms, emitting red fluorescence. Stain the extracellular polysaccharide matrix in the biofilms with FITC-ConA and keep in the dark for 30

minutes. FITC-ConA binds to the polysaccharides in the ECM, emitting green fluorescence. Images are captured using a laser scanning confocal microscope (Leica TCS SP8 STED, Leica) to observe the distribution of hyphae and polysaccharides in the biofilms.

2.4.4 Analysis of Degradation Product Composition

A microscopic infrared spectrometer (FTIR, Nicolet iN10, ThermoFisher) was used to analyze the functional groups and chemical bond information on the surface of the samples after testing. The test was conducted using the attenuated total reflectance (ATR) mode, with the ATR crystal being a germanium internal reflection element. At least 25 spectra were recorded for each area, with 64 scans, a resolution of 8 cm^{-1} , and a range of $750 - 4000\text{ cm}^{-1}$. Characteristic absorption peak information was obtained by collecting in-situ infrared spectra on the sample surface, and the spectra were analyzed using Nicolet Omnic (v. 9.2) software.

2.4.5 Analysis of Corrosion Residue Characteristics on Degradable Material Surfaces

The samples were immersed in sterile water, and surface mycelia were removed using an ultrasonic method. They were then rinsed with deionized water, dehydrated with anhydrous ethanol, and dried in an inert atmosphere. The surface micro-corrosion residue morphology was subsequently observed using a field emission scanning electron microscope (SEM, GeminiSEM 300, Zeiss, Germany).

2.4.6 Insulation Test of Materials

According to the IEC 62631–3-1 standard, the ST2643 ultra-high resistance microcurrent tester is used, along with the ST2643-F02 ring-type three-electrode device, to test the volume resistivity of samples after the experiment. To ensure the accuracy and reliability of the test results, three different positions are selected on each group of samples for repeated testing.

3 Results

3.1 Targeted Metabolomic Analysis

By measuring the concentration of organic acids secreted by *Aspergillus*

brasiliensis on silicone rubber samples under different environments, the differences in the impact of organic acid concentration on sample degradation can be reflected. LC-MS was used to qualitatively and quantitatively analyze the fungal metabolites in the eluent from the sample culture chamber. As shown in Figure 2, the total amount of organic acids secreted by *Aspergillus brasiliensis* in the terrestrial environment was an order of magnitude higher than that in the space environment, and under both terrestrial and space conditions, this strain could secrete multiple organic acids. Considering the contribution of organic acid concentrations to the total amount of organic acids under both conditions, the top four organic acids were butyric acid, oxalic acid, lactic acid, and adipic acid. The difference in organic acids between the two environments was mainly in butyric acid; that is, in the terrestrial environment, *Aspergillus brasiliensis* secreted a large amount of butyric acid on the material surface. Butyric acid (-COOH) has certain compatibility with silicone rubber sheets (Si-O-Si)^[22], making it easy to penetrate into the rubber. Butyric acid is weakly acidic, and in the terrestrial environment, the excess amount of butyric acid led to excessive acidity on the sample surface, resulting in acidic degradation of the material in the terrestrial environment^[23].

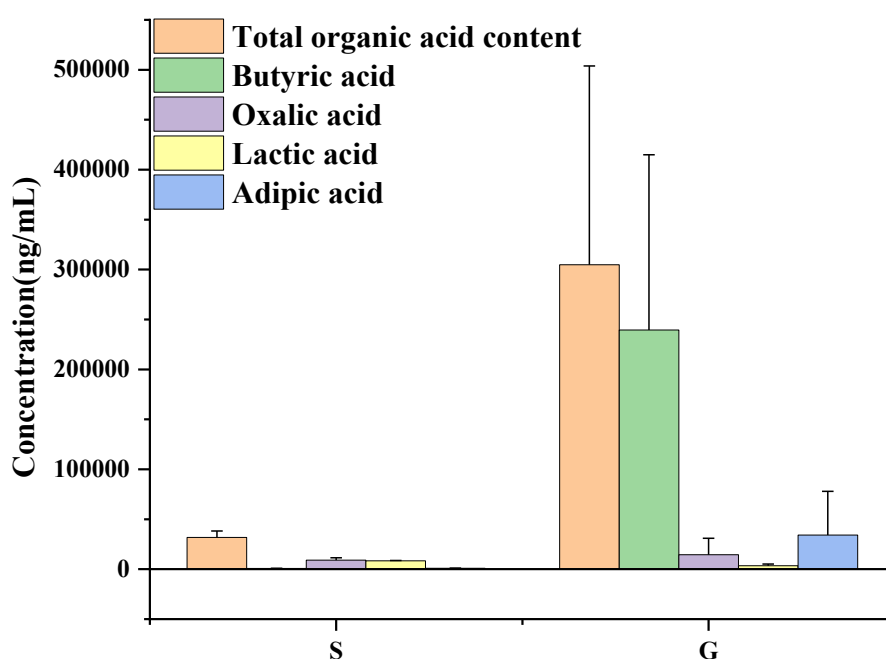


Figure 2 Main organic acids secreted by *Aspergillus brasiliensis* on the surfaces of spatial

samples (S) and ground samples (G)

3.2 Corrosion Morphology Analysis

3.2.1 Macroscopic Morphology

After conducting an *Aspergillus brasiliensis* corrosion experiment under both space and ground conditions on silicone rubber samples, the surface morphology of the samples was observed using a macro microscope. The blank control group (K group) was used as a reference for comparative analysis (Figure 3). The results showed that the surface of the blank control group samples was generally smooth and flat, with no obvious morphological defects or color changes, presenting the material's inherent uniform and dense state. No traces of microbial adhesion or surface damage induced by corrosion were detected, confirming the stability of the silicone rubber substrate under sterile conditions. Neither the space group nor the ground group experimental samples exhibited the typical hyphal networks and spore structures of *Aspergillus brasiliensis* on the surface; only a large number of evenly distributed circular marks were observed. These circular marks may be traces left after the nutrient solution dried, representing a direct indication of microbial colonization, growth, and extracellular polymeric substance (EPS) secretion on the material surface. The color of the circular marks on the ground group samples was significantly darkened, with the dark areas corresponding to the deposition and enrichment of *Aspergillus brasiliensis* spores (Figure 3(c3)). Although the acidic metabolites secreted did not cause macroscopically visible large-scale corrosion pits, they had already induced changes in the surface microstructure through interfacial interactions. The formation of dark marks provides important morphological evidence for the subsequent in-depth study of microbial corrosion and also reflects the staged characteristics of the silicone rubber surface response under the corrosive environment of *Aspergillus brasiliensis*.

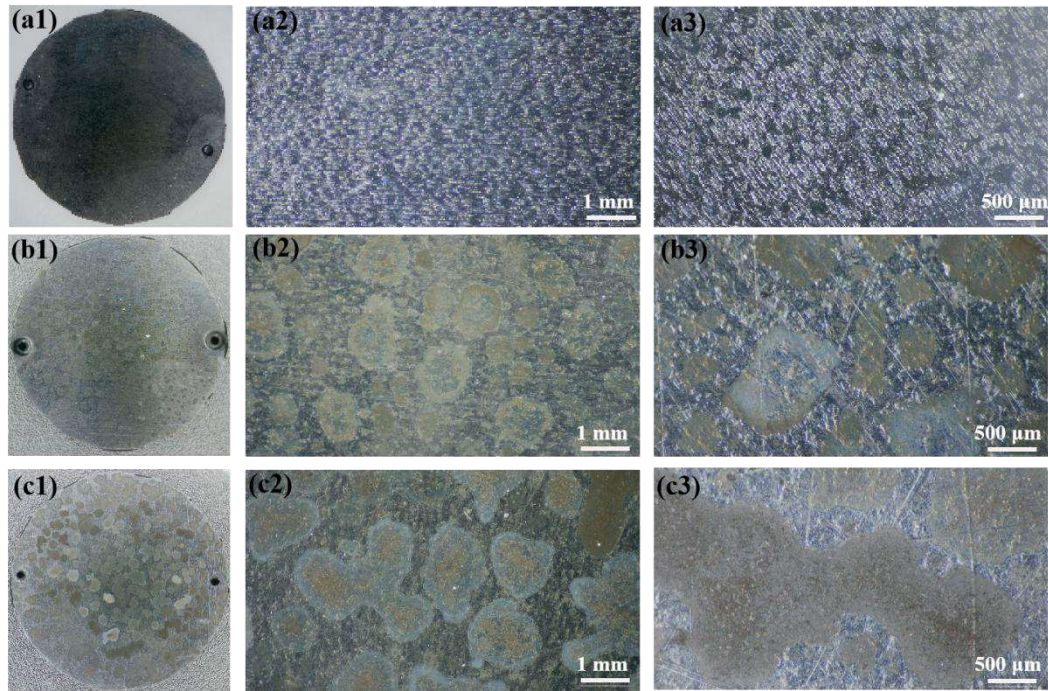


Figure 3 Optical microscope images of biofilm adhered to the surface of silicone rubber samples, (a) control group, (b) space group, (c) ground group

3.2.2 Stereomicroscopy and Laser Confocal Microscopy Morphology Analysis

To more intuitively reveal the spatial distribution characteristics of corrosion morphology, stereomicroscopic techniques were used to observe the surface morphology of the samples, and the results are shown in Figure 4. In the spatial group samples, there were a small number of microcracks and shallow pits on the surface of the spore aggregation area, but the processing marks on the sample surface were still visible, indicating that the surface morphology degradation of the spatial group samples was minor. In comparison, the surface morphology degradation of the ground group samples was more pronounced, with significantly larger pits and obviously higher surface roughness.

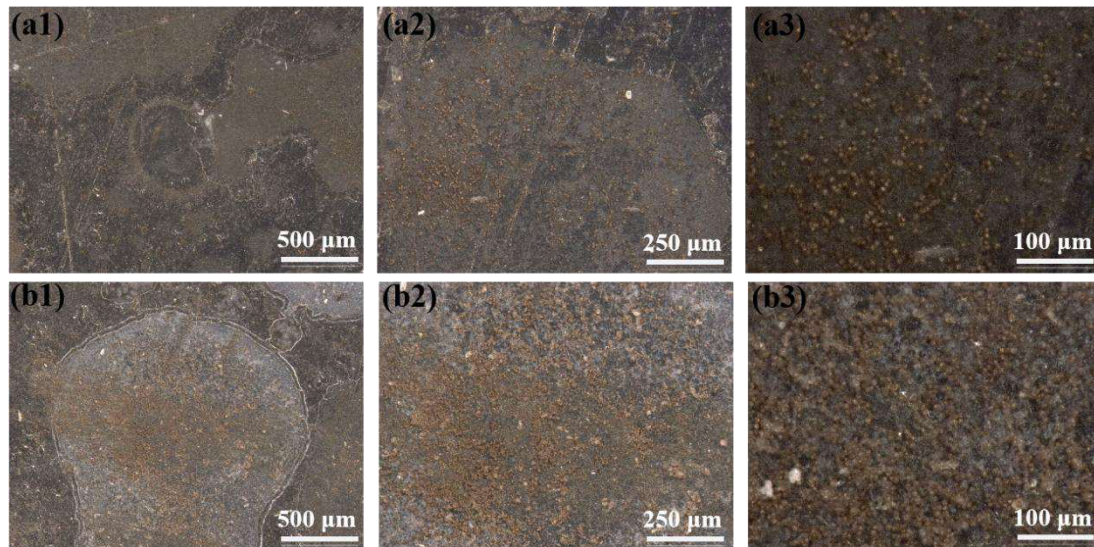


Figure 4 Optical microscope images of biofilm adhered to the surface of silicone rubber samples; (a) Space environment, (b) Ground environment

In order to further characterize the microscopic morphology and three-dimensional distribution features of silicone rubber surfaces under different environments, laser confocal microscopy was used to perform three-dimensional surface scans of the samples, as shown in Figure 5. The results show that samples from the ground group had dense biofilm attachment, and no obvious aging phenomena were observed on the samples themselves; the space group samples exhibited two types of morphology, namely regions with dense biofilm enrichment and regions with fewer spores exposing the underlying material. In the areas where the base material was exposed, noticeable aging and cracking of the sample itself were observed. Since there were fewer spores in these areas, it is likely that these regions were not covered by biofilm and therefore underwent hydrolysis.

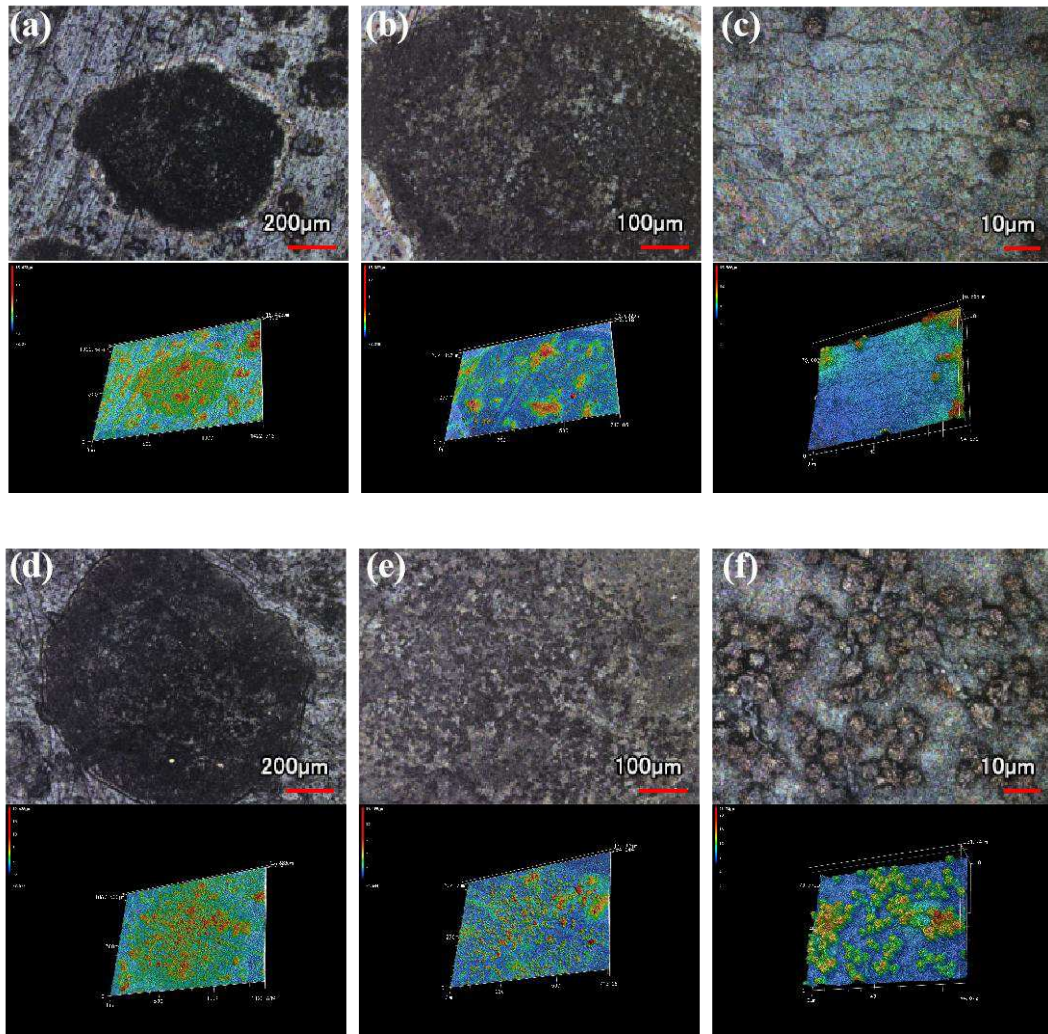


Figure 5 Laser confocal microscopic morphology of the surface of silicone rubber samples, (a~c) spatial samples; (d~f) ground samples

3.2.3 SEM Micro-morphology Analysis

To further characterize the microscopic morphological features of silicone rubber surfaces under different environments, a scanning electron microscope (SEM) was used for high-magnification observation of the sample surfaces, and the results are shown in Figure 6. From the microscopic morphology images, it can be seen that the surfaces of samples in both environments display relatively obvious circular droplet traces left by the nutrient solution. The interior of the circles is covered with spore suspension, while the outer areas are regions where *Aspergillus brasiliensis* was not inoculated. It was observed that no hyphal morphology was seen on the silicone rubber sample surfaces, only a large number of spores. In the space group samples, a

large number of spores were only found at the edges of the circular traces, whereas in the ground group, the interior of the circular traces was covered with a large number of spores. The enrichment of spores at the edges in the space group may also be related to the edge effect ^[24]. In a microgravity environment, the effect of gravitational sedimentation is essentially eliminated, and spores are no longer driven by downward gravity. At this time, liquid movement is mainly dominated by surface tension gradients (Marangoni effect). This fluid state makes it difficult for the spore suspension to spread evenly as it does on the ground. The surface tension gradients are strongest at the droplet edges, making them the “preferred areas” for spore migration and adhesion. Therefore, in terms of spore enrichment, the surface of the ground group has more spores than the space group. At higher magnification, it was found that the spores on the surface of the ground group samples had two morphologies: the first type has spores adhering to each other with no hyphae (Figure 6(e)), and the second type has hyphae growing in certain areas (Figure 6(f)). The degree of spore adhesion on the surface of the space group samples was significantly lower than that of the ground group. In the droplet traces of the space group samples, surface cracks could still be seen around the spores, which is consistent with the macroscopic morphology results shown in Figure 5(c).

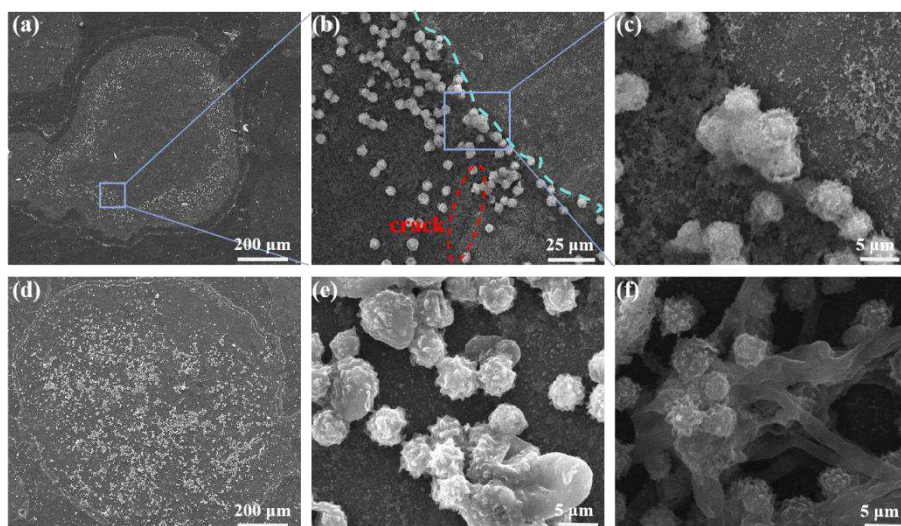


Figure 6 SEM micrographs of the surface of silicone rubber samples, (a~c) spatial samples; (d~f) ground samples, among which (e) and (f) are parts inside the droplet in (d)

3.3 Fluorescence Staining Analysis

In order to gain a deeper understanding of the adhesion mechanism of *Aspergillus brasiliensis* biofilms in microgravity environments, fluorescent staining was used to distinguish between hyphae and extracellular polysaccharides within the biofilm. Figure 7 shows fluorescent staining images of silicone rubber samples under different conditions, where the red channel stains the overall three-dimensional morphology of inactivated biofilms, and the green channel FITC-ConA staining primarily targets the extracellular polysaccharide matrix secreted by *Aspergillus brasiliensis*. As mentioned earlier, there is no obvious hyphal structure on the surface of the silicone rubber samples (Figure 6), meaning the main biofilm morphology on the sample surface is in spore form, which is also reflected in the fluorescent staining results. The space group samples show only slight staining signals, indicating very low bioactivity; whereas although hyphae are not visible on the surface of the ground group samples, clustered red dot signals and green channel signals distributed around them can be observed. This indicates that *Aspergillus brasiliensis* in the ground environment is somewhat active and can secrete a certain amount of extracellular polysaccharides. This is also consistent with the previous laser confocal and scanning electron microscopy results, showing that *Aspergillus brasiliensis* in the ground group exhibits stronger growth and bioactivity, with a greater potential for material degradation.

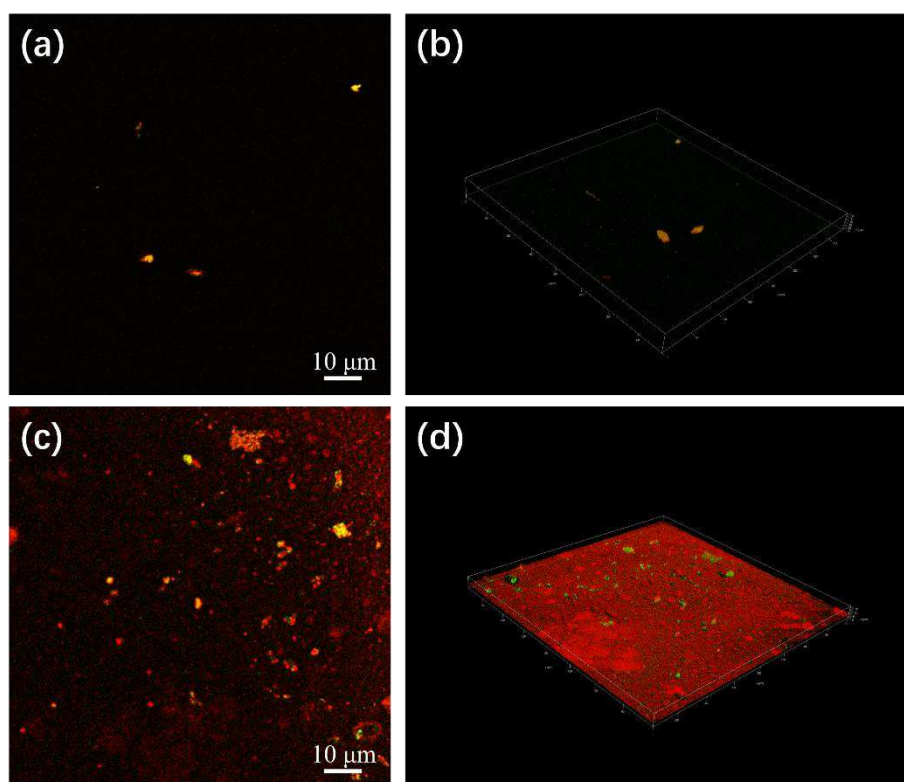


Figure 7 Fluorescent staining images of silicone rubber samples, (a~b) spatial samples; (c~d) ground samples

3.4 Material Degradation Product Analysis

3.4.1 Micro-infrared Spectroscopy Analysis

To investigate the degradation behavior and chemical structure changes on the surface of silicone rubber samples under different environmental conditions, this study used microscopic infrared spectroscopy to characterize the functional groups and chemical bonds on the surfaces of the tested samples, and the results are shown in Figure 8. Infrared spectral analysis results indicate that the space samples and ground control samples show significant degradation compared to the blank group samples. From the main methylene absorption peaks in the figure, it can be seen that the absorption peak intensity of the samples in the ground environment is lower than that in the space environment; that is, in areas of the ground environment covered by the *Aspergillus brasiliensis* biofilm, the degradation is more severe. Since methylene is usually a stable group, the methylene peak at 2915 cm^{-1} is used as a reference. By comparing the ratio of the peak areas of absorption peaks such as C=O, C=C, and C-H to the methylene peak area, the biodegradation of silicone rubber samples can be

semi-quantitatively analyzed. It can be observed that for the ground group, the indices of C=O and C-H are relatively high, meaning that compared to the blank samples and space group, the content of these two functional groups has increased. From Figure 8 and Table 2, it can also be seen that the ground group samples basically no longer have a C=C absorption peak, with the peak at this position being very weak, and the corresponding index is very small, much lower than that of the blank group and space group. It is speculated that the biodegradation of silicone rubber mainly targets the C=C functional group, meaning that mold can degrade C=C and produce products containing C=O and C-H.

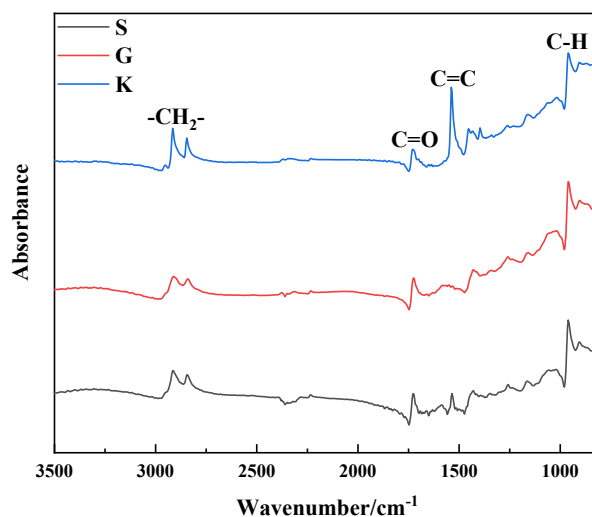


Figure 8 FTIR spectra of silicone rubber samples after biodegradation in different environments

Table 2 Semi-quantitative comparative analysis of functional groups in the samples

	A	B	C	D	B/A	C/A	D/A
	-CH ₂ -	C=O	C=C	C-H			
S	1.209	0.899	0.371	2.002	0.74	0.31	1.66
G	0.955	1.289	0.011	1.986	1.35	0.01	2.08
K	1.411	1.142	2.57	1.606	0.81	1.82	1.14

3.4.2 Degradation Morphology Analysis

Figure 9 shows the scanning electron microscope (SEM) morphology characterization results of silicone rubber samples after mold corrosion and complete

removal of surface mold. As shown in Figure 9 (a-b), the surface of the blank control sample is generally smooth and flat, with no obvious corrosion damage, pores, or structural destruction, indicating that the silicone rubber matrix structure is intact and the surface state is stable without mold invasion. In contrast, both the ground group and the space group samples show varying degrees of surface damage. As shown in Figure 9 (c-d), the surface of the ground group sample is generally flaky, with a severe degree of biodegradation of the rubber, and the surface is no longer flat; whereas as shown in Figure 9 (e-f), the surface of the space group sample is still relatively flat overall, but there are a few flakes and long cracks on the surface. Therefore, the degradation effect of *Aspergillus brasiliensis* on silicone rubber is greater in the ground environment than in the space environment.

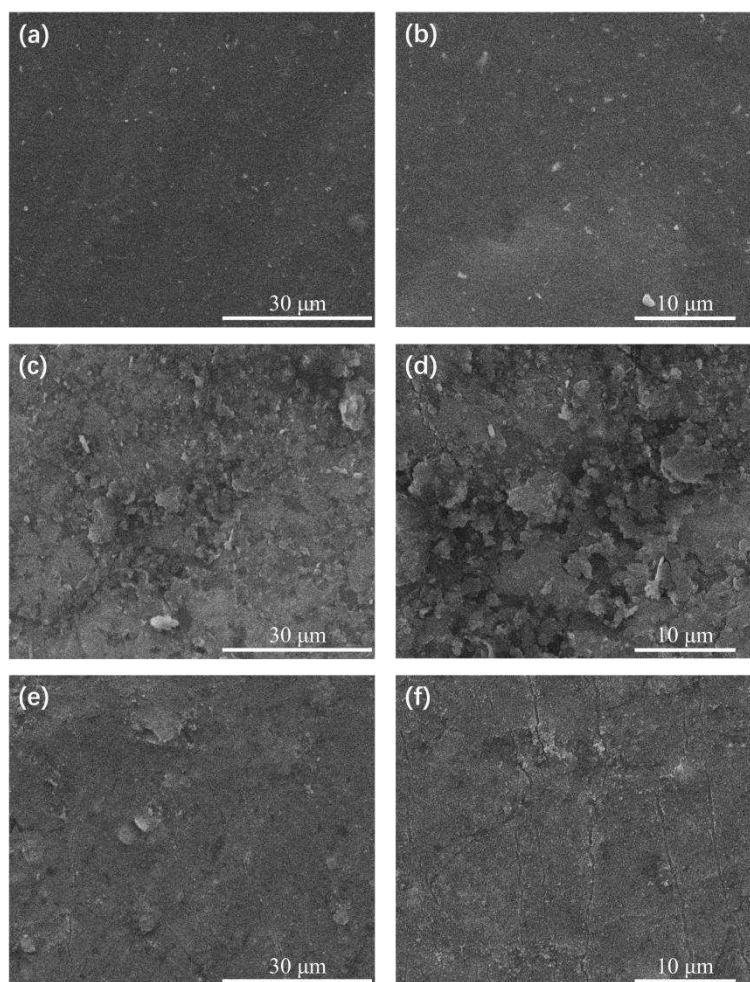


Figure 9 SEM images of the silicone rubber sample surfaces after sterilization, (a-b) blank samples; (c-d) floor samples; (e-f) air samples

3.4.3 Insulation Test Analysis

Figure 10 shows the volume resistivity test results of silicone rubber samples under different environmental conditions, where group S is the space group, group G is the ground group, and group K is the blank control group. As can be seen from the figure, there are significant differences in volume resistivity among the three groups: both the blank control group (K) and the space group (S) maintain a volume resistivity of approximately 600 $\text{k}\Omega\cdot\text{cm}$, with similar values and consistent fluctuation ranges; in contrast, the volume resistivity of the ground group (G) drops sharply to about 330 $\text{k}\Omega\cdot\text{cm}$, nearly 50% lower than that of the blank and space groups. This result is highly consistent with previous characterization data such as infrared spectroscopy and organic acid metabolism, further confirming the corrosive effect of microorganisms on the material from an electrical performance perspective. Specifically, under Earth's gravity, the degradation effect of *Aspergillus brasiliensis* on silicone rubber is more pronounced. The organic acids (such as butyric acid) produced by *Aspergillus brasiliensis* through metabolism catalyze the hydrolytic cleavage of the Si-O-Si bonds in the silicone rubber main chain, simultaneously disrupting the material's cross-linked network structure, introducing a large number of polar silanol groups (Si-OH) and conductive ions ^[25], ultimately resulting in reduced carrier migration resistance within the material, which macroscopically manifests as a significant decrease in volume resistivity and deterioration of insulation performance.

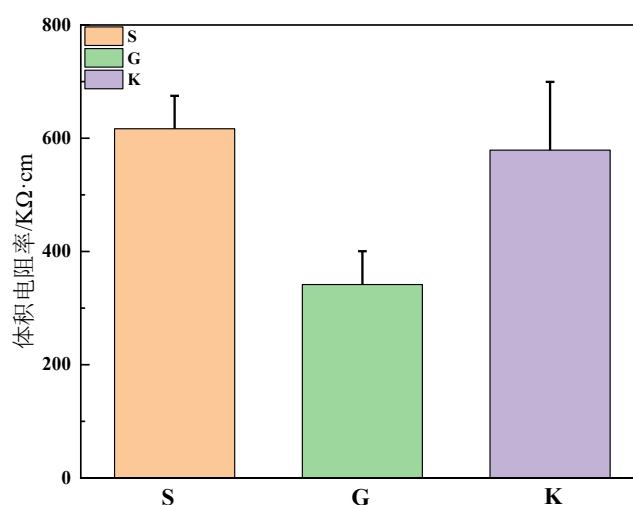


Figure 10 Comparison of Volume Resistivity of Silicone Rubber Samples

4 Discussion

Through targeted metabolomics, fluorescence staining analysis, multi-scale morphological characterization, and chemical structure analysis, the differences in the corrosion and degradation behavior of silicone rubber induced by *Aspergillus niger* under space microgravity and ground gravity environments are investigated from the perspectives of gravity effects and fungus-induced degradation mechanisms.

4.1 Mechanism of Microgravity on the Degradation of Silicone

Rubber

The morphological characterization results from the space-ground comparative experiment revealed that the microgravity environment significantly inhibits the surface corrosion and colonization efficiency of *Aspergillus brasiliensis* on silicone rubber. As shown in Figure 3(c), macroscopic observation indicates that the surface of the ground samples exhibits obvious dark circular marks, signifying extensive spore deposition and enrichment, and inducing changes in the surface microstructure through the secretion of metabolic products; whereas in Figure 3(b), the space samples only show faint traces, with surface color showing no significant difference from the substrate, and microbial attachment is strictly limited. Stereomicroscopy and laser confocal analysis further quantified this environmental difference (Figures 4–5): the ground samples exhibit significant surface degradation, with dense pits and high roughness; though the space samples have localized microcracks, the initial markings on the substrate are still visible, demonstrating the material's corrosion resistance advantage under microgravity.

SEM microscopic morphology clearly illustrates the effect of microgravity. Microgravity eliminates the gravity-driven sedimentation of spores, causing the movement of spore suspensions to shift from gravity-driven convection to being dominated by surface tension gradients (Marangoni effect). This fluid state prevents the spores from spreading evenly within the droplets, concentrating only at the edges due to strong tension gradients, showing an "edge effect" characteristic. In contrast, the ground spores aggregate due to gravity-driven sedimentation collisions, forming

large-area, highly adherent dense spore layers within the droplets. Additionally, the surface cracks surrounding the space spores corroborate that insufficient spore adhesion under microgravity leads to localized hydrolysis, failing to form a complete biofilm coverage.

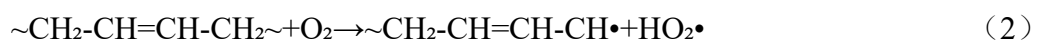
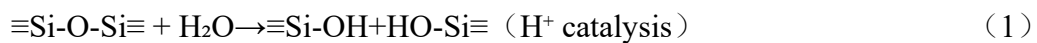
4.2 Material Degradation Mechanisms Induced by Microorganisms

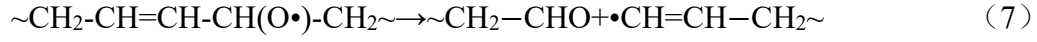
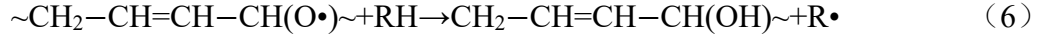
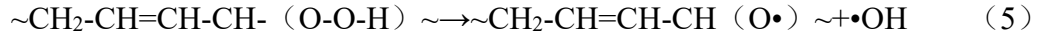
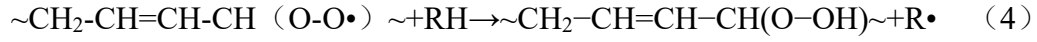
Aspergillus brasili's degradation of silicone rubber is mainly achieved through metabolic secretion of organic acids. Multidimensional characterization from ground-ground control experiments shows that microgravity environments significantly regulate the metabolic activity and material degradation efficiency of *Aspergillus brasili*, forming differentiated microbial-induced degradation mechanisms. The core differences stem from the synergistic effects of organic acid secretion characteristics, chemical structure destruction of materials, and surface morphology degradation.

Crosslinked polyethylene studied by Zhang Shuyuan et al. ^[26], PCB polyurethane coating by Liu Qianqian et al. ^[20], and beryllium bronze studied by Song Xiaowen et al. ^[27] et al. As relatively hydrophilic or moderately polar hard surfaces, the total organic acid content in the spatial group was greater than that in the ground group. Silicone rubber is a hydrophobic, low surface energy, and soft material. Under microgravity, the water film is discontinuous, making it difficult to form a stable extracellular polysaccharide matrix on the surface of silicone rubber. In contrast, the ground group, due to gravity, has a stronger mold colonization and growth ability due to the material surface being soaked in droplets, with a higher content of extracellular polysaccharide matrix and a greater total amount of organic acids secreted from the material surface.

The organic acids secreted by *Aspergillus brasili* are the key mediators inducing the degradation of silicone rubber. Quantitative and qualitative analysis by LC-MS confirmed that the total amount of organic acids secreted by *Aspergillus brasili* under ground environments is an order of magnitude higher than in spatial environments, with butyric acid being the core component responsible for the

degradation differences between Earth and Earth. The carboxyl group (-COOH) in the butyric acid molecule exhibits good polar compatibility with the Si-O-Si structure of the silicone rubber backbone, and can adsorb into the material through dipole-dipole interaction with hydrogen bonds, causing sample swelling ^[28]. Its weak acidity provides the H catalytic site, initiating the hydrolysis cleavage of the Si-O-Si main chain ^[25], as shown in Formula 1. The sample undergoes swelling, accelerating oxygen diffusion into the material. In an oxygen-rich environment, the methylene group (-CH₂-) in the silicone rubber molecular chain undergoes hydrogen loss reactions, generating alkyl radicals (CH₂-CH=CH-CH•) and superoxide radicals (HO₂•) ^[29], as shown in formula 2. Subsequently, alkyl radicals rapidly combine with oxygen to form peroxyradical intermediates ^[30], as shown in formula 3. Peroxy radicals further undergo intramolecular rearrangement and hydrogen transfer reactions, forming unstable peroxide intermediates, as shown in formula 4. The peroxide intermediate continues to decompose, producing alkoxy radicals and carboxyl radicals, as shown in formula 5. Alkoxide radical decomposition can produce oxygen-containing products containing alcohols, ketones, and aldehydes, as shown in formulas 6 and 7. The formation of ketone- and aldehyde-containing oxygen-containing products involves the breakage of carbon-carbon double bonds (C=C) or carbon-carbon single bonds (C-C), causing a significant decrease in the number-average molecular weight of silicone rubber. The final degradation products are small molecular chain segments, carbonyl groups (C=O), and other oxygen-containing functional groups. The degradation mechanism diagram of silicone rubber under *Aspergillus* Brazil is shown in Figure 11. Microscopic infrared spectroscopy also showed a significant increase in the content of C=O and C-H functional groups in the ground group samples, while the absorption peak of C=C functional groups almost disappeared, further supporting the above degradation process.





on the ground

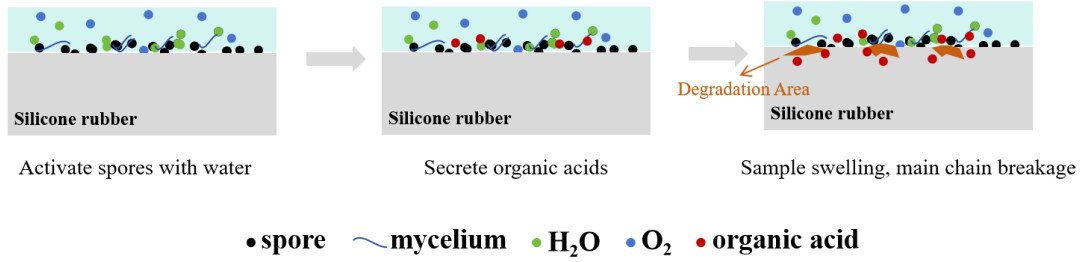


Figure 11 Mechanism diagram of silicone rubber degradation under *Aspergillus brasiliensis* action

The large secretion of butyric acid in the ground environment significantly increases the acidity on the material surface, forming a strongly acidic microenvironment, which not only accelerates the acidic hydrolysis of the silicone rubber main chain but also promotes the oxidative cleavage of carbon-carbon double bonds through a swelling-oxygen enrichment effect, creating a dual degradation synergistic effect. In contrast, in the space environment, the secretion of butyric acid is extremely low, and the acidic catalytic effect is significantly weakened, which is the key reason why the material degradation in space is less than that on the ground.

5 Conclusions

This study systematically reveals the differences in the corrosion and degradation behavior of silicone rubber induced by *Aspergillus brasiliensis* under space microgravity and terrestrial gravity environments. The experimental results show:

(1) The total amount of organic acids secreted by *A. brasiliensis* in the terrestrial environment far exceeds that in the space environment, leading to an acidic surface on the terrestrial samples and more pronounced degradation. Fluorescence staining analysis also confirmed that *A. brasiliensis* exhibits certain activity in the terrestrial

environment and is capable of secreting some extracellular polysaccharides.

(2) Multi-scale morphological characterization found that no mycelium was present on the surface of any samples, with only spores present. Spores on terrestrial samples were highly concentrated and adhered to each other, whereas spores on space samples were sparsely distributed, mostly attaching individually to the samples.

Micro-infrared detection results showed that the majority of the infrared spectra in the terrestrial and space control environments were consistent, but the absorption peaks at positions such as methylene and carbon-carbon double bonds varied. Semi-quantitative analysis indicated a higher degree of material degradation in the terrestrial environment. SEM characterization after removing mold and corrosion products showed that the surface of terrestrial samples appeared generally fragmented and was no longer smooth, whereas the surface of space samples remained relatively smooth with only a small amount of debris. Volume resistivity further confirmed the microbial corrosive effects on the material from an electrical performance perspective, with *A. brasiliensis* causing more significant degradation of silicone rubber in the terrestrial environment.

Acknowledgments

This work was supported by the Space Station Engineering Aerospace Technology Test Field Project (NO.2019HJS002) and the National Natural Science Foundation of China (Nos. 52371048, 51971032, and 52071019).

References

- [1] Ullah R, Akbar M, Amin S. Measuring electrical, thermal and mechanical properties of DC-stressed HTV silicone rubber loaded with nano/micro-fillers exposed to long-term aging[J]. Applied Nanoscience, 2020, 10(7): 2101-2111.
- [2] Guimont A, Beyou E, Alcouffe P, et al. Synthesis and characterization of PDMS-grafted graphite oxide sheets[J]. Polymer, 2013, 54(18): 4830-4837.
- [3] Wu Y J, Cai F J, Xu K D, et al. Study on electrical, thermal, mechanical and corrosion resistance properties of conductive silicone rubber for polymer-based metal composite grounding electrodes[J]. Journal of Materials Science: Materials in Electronics, 2024, 35(11):765.

- [4] Wang Z, Luo Z H, Ji Y M, et al. Research on Risk Management of Long-term On-orbit Operation of Space Stations and Its Implications [J]. *Manned Spaceflight*, 2025, 31(03): 285-292.
- [5] Aleksandra S C, Camilla U, Malli B G M, et al. Characterization of the total and viable bacterial and fungal communities associated with the International Space Station surfaces[J]. *Microbiome*, 2019, 7(1): 50.
- [6] Kazuo S, Takashi Y, Takako N, et al. Characterization of fungi isolated from the equipment used in the International Space Station or Space Shuttle[J]. *Microbiology and immunology*, 2016, 60(5): 295-302.
- [7] Ghamrawi S, Bouchara J, Corbin A, et al. Inhibition of fungal growth by silicones modified with cationic biocides[J]. *Materials Today Communications*, 2020, 22100716-100716.
- [8] Gu J D. Microbial colonization of polymeric materials for space applications and mechanisms of biodeterioration: A review[J]. *International Biodeterioration & Biodegradation*, 2007, 59(3): 170-179.
- [9] Nastasi N, Bope A, Meyer E M, et al. Predicting how varying moisture conditions impact the microbiome of dust collected from the International Space Station.[J]. *Microbiome*, 2024, 12(1): 171.
- [10] Balasubrahmaniam N, Nastasi N, Hegarty B, et al. Exposure to elevated relative humidity in laboratory chambers alters fungal gene expression in dust from the International Space Station (ISS)[J]. *Scientific Reports*, 2025, 15(1): 28366-28366.
- [11] Cao J N, Wang B, Niu Y, et al. Study on the Influence Mechanism of Thermal - Oxidative Aging Temperature on the Degradation Behavior and Properties of Phenyl Silicone Rubber[J]. *Journal of Applied Polymer Science*, 2026, 143(14): e70407-e70407.
- [12] Wang Z, Qian L B, Peng X Y, et al. New Aspects of Degradation in Silicone Rubber under UVA and UVB Irradiation: A Gas Chromatography - Mass Spectrometry Study[J]. *Polymers*, 2021, 13(13): 2215-2215.
- [13] Zhang X Q, Lin Z H, Xu S R, et al. Lifetime prediction and aging characteristics of silicone rubber under synergistic heat-moisture interaction[J]. *Engineering Failure Analysis*, 2025, 170109252-109252.
- [14] Wang Y R, Dou F Z, Li S H, et al. Degradation behavior and aging mechanisms

- of silicone rubber under Ultraviolet – Thermal – Humidity Coupling in simulated tropical marine atmospheric environment[J]. *Polymer*, 2025, 328128398-128398.
- [15]Gu Y, Shi Y H, Li X Y, et al. The influence of microorganisms on the hydrophobicity of silicone rubber materials [J]. *Electrical Ceramic Lightning Arrester*, 2020, (01): 166-173.
- [16]Wallström S, Karlsson S. Biofilms on silicone rubber insulators; microbial composition and diagnostics of removal by use of ESEM/EDS[J]. *Polymer Degradation and Stability*, 2004, 85(2): 841-846.
- [17]Lugauskas A, Levinskaitė L, Pečiulytė D. Micromycetes as deterioration agents of polymeric materials[J]. *International Biodeterioration & Biodegradation*, 2003, 52(4): 233-242.
- [18]Yang S F, An Q, Liu Yu P, et al. Effect and Pathway Analysis of Lewis Acid Pretreatment Accelerating *Aspergillus brasiliensis* Degradation of Silicone Rubber[J]. *Proceedings of the Chinese Society for Electrical Engineering*, 2026, 1-15.
- [19]Zhang W, Chen N, Yuan J, et al. Initial attempt: Design and application of microorganism-material interaction test on On-orbit space microgravity conditions[J]. *Acta Astronautica*, 2025, 228: 384-95.
- [20]Liu Q, Zhang W, Yuan J, et al. Study on biodegradation of polyurethane coating on PCB by *Aspergillus brasiliensis* in space[J]. *Chemical Engineering Journal*, 2024, 490: 151514.
- [21]Zhang S, Dang L, Li W, et al. Differential microbial degradation of cross-linked Polythene by *Aspergillus niger* in space and on the ground[J]. *Chemical Engineering Journal*, 2025, 509: 161394.
- [22]Wilson R F, Tilley J M A. Determination of organic acids in silage by silica gel chromatography[J]. *Journal of the Science of Food and Agriculture*, 1964, 15(4): 209-214.
- [23]Zhang N, Wang Z, Yang Y, et al. Study on the Aging Mechanism of Silicone Rubber by Nitric Acid [J]. *Transactions of Electrical Technology*, 2021, 36(22): 4820-4828.
- [24]Akshay K, Joel L P, Peter C W. Effect of capillary and marangoni forces on transport phenomena in microgravity[J]. *Langmuir: the ACS journal of surfaces and colloids*, 2015, 31(19): 5377-5386.

- [25] Marek C, Yitzhak A. Mechanism of the Acid-Catalyzed Si–O Bond Cleavage in Siloxanes and Siloxanols. A Theoretical Study[J]. *Organometallics*, 2002, 21(11): 2165-2175.
- [26] Zhang S, Dang L, Li W, et al. Differential microbial degradation of cross-linked Polythene by *Aspergillus niger* in space and on the ground[J]. *Chemical Engineering Journal*, 2025, 509161394-161394.
- [27] Song X, He Z, Chen N, et al. Corrosion behavior and mechanism of beryllium bronze induced by *Aspergillus brasiliensis* in space[J]. *Corrosion Science*, 2026, 258113421-113421.
- [28] Mazurek P, Vudayagiri S, Skov A L. How to tailor flexible silicone elastomers with mechanical integrity: a tutorial review[J]. *Chemical Society Reviews*, 2019, 48.
- [29] Kornacka E, Kozakiewicz J, Legocka I, et al. Radical processes induced in poly (siloxaneurethaneureas) by ionising radiation[J]. *Polymer Degradation and Stability*, 2006, 91(9): 2182-2188.
- [30] Schilinsky L, Jeschke G, Tschaggelar R, et al. Formation and decay of radicals during Vacuum-UV irradiation of poly(dimethylsiloxane)[J]. *Polymer Degradation and Stability*, 2017, 144497-507.