Microbes as Agents of Change: Historical, Cultural, and Astrobiological Perspectives

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Abstract

Microorganisms have repeatedly reshaped human societies, culture, and scientific knowledge in ways that extend well beyond their microscopic scale. This paper synthesizes historical, cultural, and astrobiological literature to argue that microbes function as active agents of change—biological actors whose properties (transmission, immunity, metabolism, and environmental tolerance) reconfigure demographic systems, material practices, and scientific paradigms. Section 1 examines pandemics (notably the Black Death and smallpox) to show how pathogen biology produced lasting political, economic, and social transformations. Section 2 reviews foundational microbiologists (Pasteur, Koch, Fleming) whose experiments and discoveries converted microbes from ambiguous forces into identifiable, governable entities and enabled interventions such as pasteurization, vaccination, and antibiotics. Section 3 explores microbial contributions to art and industry, highlighting bacterial agar art and fungal/yeast-derived pigments as examples of how microbes mediate creative and sustainable material practices. Section 4 extends the analysis to astromicrobiology, summarizing extremophile biology, orbital exposure experiments (e.g., EXPOSE/ADAPT), and implications for panspermia and planetary protection. Across these domains the paper emphasizes two themes: (1) microbial agency as a useful analytical lens for connecting biological mechanisms to historical and cultural outcomes, and (2) the continuing negotiation between human attempts to control microbes and microbial evolutionary responses (e.g., antibiotic resistance; contamination risks). The paper concludes by outlining ethical and research priorities—improved historical–biological integration, sustainable bio-based technologies, and strengthened planetary-protection protocols—to guide future study of microbes as active participants in planetary and human history.

Keywords: Microbial agency, Pandemic history, Germ theory, Microbial art, Fungal pigments, Astromicrobiology, Extremophiles, Planetary protection

Submission Note: Paper prepared for the Microbiology (BT321IU) course, International University - VNU-HCM.

1. Introduction

Microbes are among the most abundant and influential life forms on Earth, contributing substantially to planetary biomass and shaping ecosystems at every level despite their microscopic size, a fact that becomes especially clear when viewed through historical, cultural, and planetary perspectives.. Throughout history, microorganisms have reshaped human societies, influenced cultural practices, and catalyzed scientific breakthroughs that redefine modern life. From pandemics that altered civilizations to extremophiles that challenge our understanding of life's limits, microbes exhibit a level of ubiquity and power that is both surprising and foundational as the following sections illustrate. Microbiology, the scientific discipline devoted to the study of microorganisms, reveals the extraordinary breadth of microbial influence across both natural and human systems. As such, microbes are not simply sources of disease, but powerful drivers of historical change, cultural production, and emerging scientific frontiers such as astrobiology. Their largely unseen impact spans multiple disciplines and eras, highlighting the deep interconnectedness between microbial life and human advancement.

This paper is organized into four principal sections to examine these multidimensional contributions of microorganisms. The first explores microbes that changed history by analyzing the social and medical consequences of pandemics such as smallpox and the Black Death. The second surveys pioneering microbiologists whose discoveries transformed science and medicine, including Pasteur, Koch, and Fleming. The third investigates microbial influence in art and culture, with emphasis on bacterial art and natural dye production. The final section extends the discussion beyond Earth, examining extremophiles, microbial survival under space-like conditions, and their implications for astrobiology.

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Rather than treating microbes as passive background conditions to which humans merely respond, this paper argues that microorganisms function as active agents of change—entities whose biological properties constrain, redirect, and at times override human intentions across history, culture, and science. By shaping demographic collapse, enabling new artistic media, and redefining planetary habitability, microbes do not simply influence human systems; they actively participate in them. Viewing microbes as agents rather than environmental noise clarifies why they repeatedly reorganize social structures, cultural meaning, and scientific definitions of life itself.

2. Microbes that Changed History

This section examines the far-reaching influence of pathogenic microbes on human civilization, focusing on two specific agents that altered demographic, economic, and social structures globally. Rather than acting as passive causes of disease, these microorganisms functioned as active historical forces, reshaping political systems, economic structures, and patterns of human belief on a global scale.

2.1. The Black Death and Yersinia pestis

The Black Death, a devastating pandemic caused by the bacterium *Yersinia pestis* that peaked between 1346 and 1353, serves as a primary example of microbial impact on human history. The disease is believed to have traveled along the Silk Road from Central Asia to Europe, facilitated by the expansion of trade routes and the movement of armies [1, 2]. Upon reaching Europe, the plague caused a demographic collapse of unprecedented scale, killing an estimated 50% of the population in affected regions of Europe and Asia [3, 4].

The massive loss of life triggered profound societal and economic shifts. The sudden scarcity of labour empowered the surviving peasantry, which led to the decline of the feudal system as workers demanded higher wages and better conditions [5, 6]. The psychological trauma of the pandemic also reshaped religious and social attitudes, manifesting in extreme movements such as the flagellants and the persecution of minority groups [7, 8]. In this sense, *Yersinia pestis* acted not merely as a pathogen but as a catalyst for systemic change, accelerating social transformations that might otherwise have taken centuries.

The transmission cycle of *Y. pestis* historically involved the black rat (Rattus rattus) and the rat flea (Xenopsylla cheopis) [9]. After feeding on an infected host, Y. pestis blocks the flea's gut, causing regurgitation of bacteria into new hosts during later bites [10]. While bubonic plague was the most common form, the pneumonic form allowed direct person-to-person transmission, thereby accelerating spread. Fig. 1 provides a visualized diagram of the transmission pathway. The biological characteristics of Y. pestis—its zoonotic reservoir, vector-based transmission, and capacity for airborne spread—directly determined the speed, scale, and severity of its historical impact.

2.2. Smallpox and Global Eradication

Shifting focus to another microbial agent that fundamentally altered human history: smallpox. Caused by the Variola major virus and carrying a fatality rate of ~30%, the disease played a decisive role in the colonization of the Americas. Following the arrival of Europeans, smallpox decimated indigenous populations, such as the Aztecs and Incas, who lacked prior immunity [12]. This "virgin soil" epidemic killed tens of millions—perhaps up to 95% of the indigenous population of the Americas—far exceeding the deaths caused by warfare and facilitating the collapse of indigenous empires [13, 14].

The fight against smallpox marked the birth of immunology. In 1796, Edward Jenner observed that milkmaids who contracted cowpox (a mild disease) were immune to smallpox. He tested this hypothesis by inoculating a young boy with material from a cowpox lesion and subsequently exposing him to smallpox; the boy remained healthy [15, 16]. Jenner's work established the principle of vaccination, a term derived from vacca (Latin for cow), replacing the riskier practice of variolatio, an earlier technique that intentionally induced a mild smallpox infection to confer immunity [17].

Smallpox holds the distinction of being the first and only human infectious disease to be eradicated. Following a massive global campaign by the World Health Organization (WHO) involving vaccination, surveillance, and quarantine, the disease was declared eradicated in 1980 [18, 19]. As such, the disease marks a turning point in human–microbe relations, where scientific understanding allowed humans strategically to counter microbial influence.

Together, the Black Death and smallpox demonstrate that microbial impact is not limited to mortality statistics but extends to structural reorganization of societies. In both cases, the biological features of the pathogen—mode of transmission, immunity dynamics, and host susceptibility—directly shaped political power, labour systems, and colonial outcomes. These outcomes were not accidental side effects of disease; they were emergent properties of microbial life interacting with human networks. In this sense, microbes acted less like external shocks and more like historical actors whose constraints forced new social equilibria.

3. Famous Microbiologists and Groundbreaking Discoveries

This section examines how key microbiologists transformed microbes from invisible forces of fate into identifiable, controllable agents—thereby reshaping history, medicine, and society.

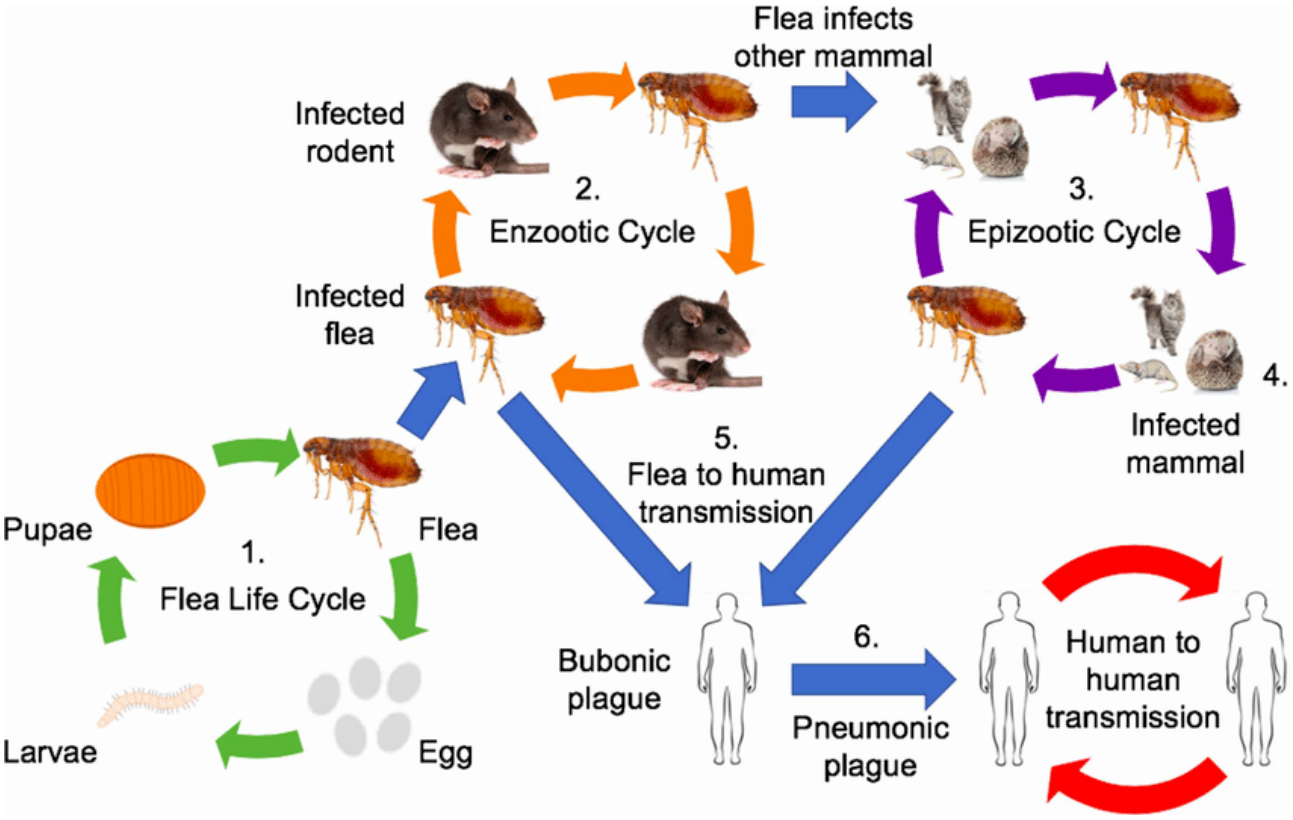

Fig. 1: Mechanisms of Plague (*Y. pestis*) Transmission and Disease Progression. The cycle begins with (1) the Flea Life Cycle: Eggs, laid in moist soil/burrows, hatch into larvae that feed on rodent feces and develop into pupae and adult fleas. Infected adult fleas parasitize rodents. (2) The Enzootic Cycle maintains *Y. pestis* among rodent hosts and reservoirs, primarily vectored by fleas (*X. cheopis*, *X. brasiliensis*, and *S. fonquerniei*). (3, 4) Epizootic Spills occur when fleas infect non-host mammals, which often lack resistance, rapidly succumb to the disease, and spread the plague geographically. (5) Human Zoonotic Transmission: Humans are typically infected via the bite of an infected flea from a rodent or secondary mammal host. (6) Human-to-Human Spread: Bubonic plague may progress to a highly contagious pneumonic plague via lung infection, enabling *Y. pestis* transmission through infectious respiratory droplets generated by coughing. Reproduced from Mackay-Alderson J, Quastel M, Wilson E, Bellamy D [11].

3.1. Louis Pasteur: A Core Founder of Modern Microbiology

3.1.1. Germ Theory

Louis Pasteur, a French chemist, fundamentally changed biological thinking by experimentally overturning the idea of spontaneous generation. Using swan-necked flasks, he showed that microorganisms from the air—not a mysterious "vital force"—caused contamination of sterile broth (see Fig. 2). His work provided crucial support for the germ theory of disease, which holds that specific, often invisible microbes are responsible for specific illnesses [20, 21].

3.1.2. Pasteurization

Beyond theory, Pasteur applied his insights to practical problems in the wine and silk industries. He demonstrated that controlled heating of liquids (commonly in the range of 60–90°C) could kill spoilage organisms without destroying the product. This process—pasteurization—transformed food safety and remains widely used today for milk and other beverages [23].

3.1.3. Vaccine Development

Pasteur also pioneered the creation of attenuated vaccines. He developed weakened strains to protect animals from chicken cholera and anthrax, and in 1885 produced a vaccine against rabies that was successfully used to treat Joseph Meister, a boy bitten by a rabid dog [24, 25, 26]. These achievements established vaccination as a practicable medical strategy and expanded the possibilities for disease prevention.

3.2. Alexander Fleming: The Serendipitous Discovery

3.2.1. Discovery of Penicillin

In 1928 Scottish bacteriologist Alexander Fleming made a chance observation that launched the antibiotic era. Returning from a holiday, he noticed that a mold (*Penicillium notatum*) contaminating a Petri dish had produced a clear zone where *Staphylococcus* bacteria failed to grow. From this observation he identified an antibacterial substance produced by the mold [27].

3.2.2. Impact on Medicine

Fleming named the active compound penicillin. Although large-scale production was achieved later by

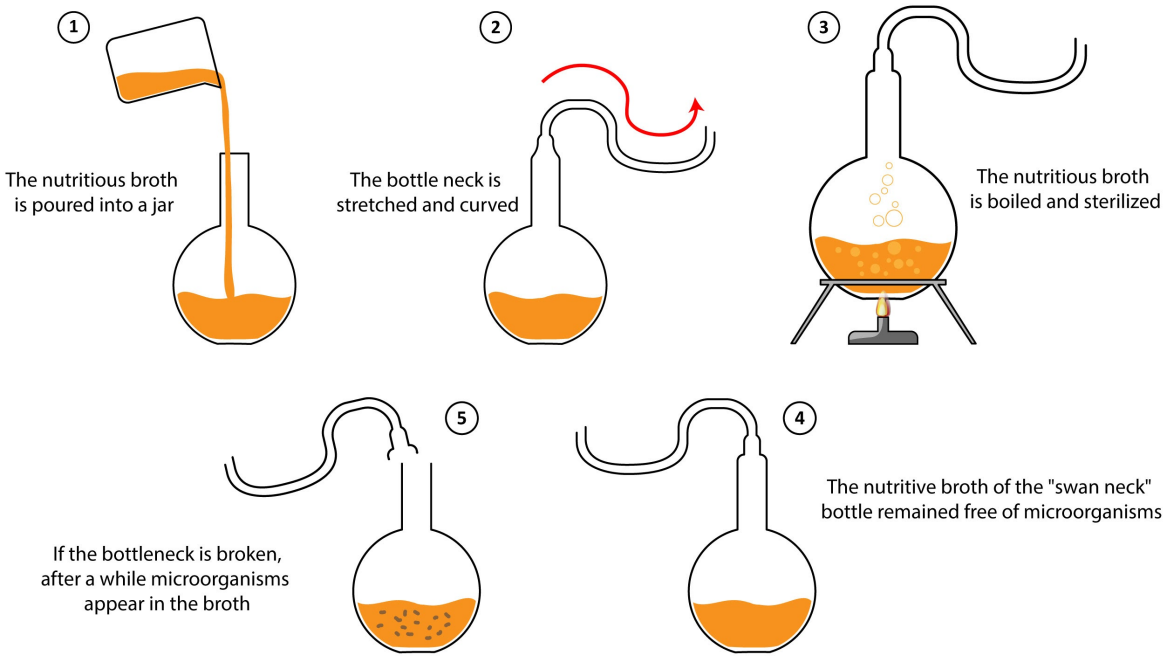

Fig. 2: Pasteur's swan-necked flask experiment illustrating how airborne microorganisms, rather than a "vital force," contaminate sterile broth. Reproduced from Shutterstock [22].

Howard Florey and Ernst Chain during World War II, Fleming's discovery provided the first effective chemical therapy for many previously lethal bacterial infections [28]. Penicillin was widely celebrated as a "miracle drug" that saved millions of lives from wound infections and diseases such as pneumonia and syphilis. Importantly, Fleming also cautioned early on about the risk of antibiotic resistance, a concern that remains central to medicine today [29].

3.3. Robert Koch and Koch's Postulates

3.3.1. Methodological Rigor

Robert Koch, a German physician, brought methodological rigor to medical microbiology and is often cited alongside Pasteur as a founding figure. He formulated what became known as Koch's Postulates: (1) the microbe must be present in every case of the disease; (2) it must be isolated and grown in pure culture; (3) inoculation of the culture into a healthy host must reproduce the disease; and (4) the same microbe must be reisolated from the experimentally infected host. These criteria established a clear framework for proving causal relationships between microbes and disease. [30, 31].

3.3.2. Key Discoveries

Applying these methods, Koch identified the causative agents of several major diseases, including *Bacillus anthracis* (anthrax), *Vibrio cholerae* (cholera), and *Mycobacterium tuberculosis* (tuberculosis) [32, 33, 34]. His work provided strong, empirically grounded support for germ theory and established standards that shaped diagnostic microbiology for generations. At the same time, the limits of Koch's Postulates—particularly for viruses, unculturable organisms, and polymicrobial diseases—are now well recognized.

Pasteur, Koch, and Fleming are sometimes presented as isolated geniuses, but their collective legacy is best understood as a transformation of microbes from mysterious forces into governable biological actors. Germ theory reframed disease as a biological interaction amenable to investigation; antibiotics redefined clinical survivability; and laboratory standards stabilized microbial knowledge across institutions. The contemporary challenge of antibiotic resistance underscores that microbes continue to evolve in response to human interventions, reminding us that microbial agency remains an active and ongoing negotiation rather than a problem already solved.

4. Microbes in Art and Culture

This section explores the scientific mechanisms underlying microbial involvement in aesthetic and cultural domains, focusing on bacterial pigment production as a medium for art and the role of fungi and yeasts in creating sustainable dyes for textiles.

4.1. Bacterial Art and Bio-Painting

Bacterial art is a form of art resulting from the special combination of microbiology with the power of visual expression by utilizing the Petri dish as a living canvas. This practice is not merely decorative; it is rooted in microbiology. The vivid colors and patterns seen in agar plate artworks arise from biological processes. Many bacteria produce secondary metabolites that are pigmented, and these pigments manifest as visible dyes when the bacteria grow on agar medium. Examples include prodigiosin from *Serratia marcescens* and violacein from *Chromobacterium violaceum*, both vivid secondary metabolites. This makes such bacteria useful as natural "biological dyes" and effective educational tools [35].

A defining feature of bacterial art is its capacity to translate invisible biochemical processes into visually interpretable patterns, making it an effective tool for both scientific inquiry and artistic expression. Pigment synthesis is tightly regulated by microbial metabolism, so colony color and spatial patterns directly reflect environmental factors such as temperature, nutrient composition, oxygen availability, and cell density. For example, prodigiosin production in *Serratia marcescens* varies with culture conditions, meaning that shifts in pigment intensity, colony morphology, or spatial growth patterns serve as intuitive indicators of metabolic state [36]. This ability to convey molecular processes transforms agar art into a functional platform for observing metabolic regulation in real time.

Agar art also inherently showcases microbial diversity. Standard culture techniques (streak plates, spread plates, dilution plating) often reveal multiple pigment-producing bacteria capable of generating carotenoids, phenazines, pyocyanin, and other chromogenic metabolites. When species or strains grow in proximity, their interactions—whether competitive, inhibitory, or cooperative—become visually evident through inhibition zones, pigment suppression, or enhanced coloration. These pigment-mediated interactions have ecological significance because microbial pigments often serve protective or competitive functions (e.g., UV shielding, antioxidant defense, antimicrobial activity). The visual nature of agar art has made it an effective tool for science communication and education: studies show that engaging with microbial art can improve students' culturing proficiency and their understanding of microbial physiology, colony morphology, and ecological dynamics [37, 38]. Public exhibitions, such as the microbial displays at ARTIS-Micropia (see Fig. 3), demonstrate how visually compelling microbial patterns engage broader audiences while conveying core scientific principles.

Beyond its artistic and educational roles, bacterial art has practical applications—most notably, the use of microbial pigments for textile dyeing. Chromogenic bacteria used in agar art (e.g., *Serratia marcescens*, *Chromobacterium violaceum*) have been studied as sustainable dye sources [39, 40]. *Serratia marcescens* produces prodigiosin, a red prodiginine pigment that has been used successfully in textile coloring [41], while *Chromobacterium violaceum* produces violacein, a violet/blue bisindole pigment [42]. Fig. 8 shows dyeing results using *C. violaceum*-derived pigment on different fabrics with alum as mordant.

Biopainting extends bacterial art by harnessing biotechnology and synthetic biology to generate colors and images on culture media. Engineering *Escherichia coli* to express a palette of eukaryotic chromoproteins creates vividly colored colonies visible in ambient light, demonstrating that synthetic circuits can be read out as visible color patterns (see Fig. 4). When "painted" onto agar, these patterns directly reflect the activity of specific genes or circuits, allowing researchers to track gene expression, environmental responses, or circuit activation without specialized instrumentation. This approach highlights how biopainting can function as a simple, observable readout for synthetic gene circuits [43].

4.2. Fungi in Pigmentation and Textiles

Fungi are a valuable source of natural pigments spanning a broad spectrum—yellow, orange, red, purple, blue, brown, and black. Important producers include *Monascus* spp. (red, yellow, orange), *Penicillium* spp. (red, yellow, brown), *Aspergillus* spp. (yellow, brown), *Fusarium* spp. (pink, violet, red), and *Blakeslea trispora* (β-carotene) [44, 45]. For example, *Penicillium brevicompactum* can produce mixtures of yellow, orange, and red pigments, while *Penicillium purpurogenum* produces red pigments that effectively dye wool, silk, polyester, and viscose (see Fig. 5).

Beyond aesthetic value, these pigments demonstrate microbes' broader impact on human life: microorganisms are harnessed for food, medicine, creative industries, and industrial applications. Fungi and lichens supplied natural dyes for centuries: species in *Roccella* and *Ochrolechia* were historically used for purples and violets, and various lichens produced dyes widely used in Europe from the 15th to 17th centuries [44]. Contemporary practices have evolved toward industrial fermentation processes that produce bio-dyes for today's sustainable textile market [47].

Fungal pigments offer a sustainable alternative to many synthetic dyes by reducing environmental pollution and health hazards associated with chemical processing. Many fungal pigments are water-soluble and amenable to fermentation-based scale-up, which can lower solvent use and environmental burden compared with some synthetic dye processes (see Fig. 6). Tables 1 and 2 summarize fungal pigments produced at industrial scale and their textile applications.

5. Bacteria in Space (Astromicrobiology)

Astromicrobiology investigates how microorganisms such as bacteria and archaea survive, adapt, and behave

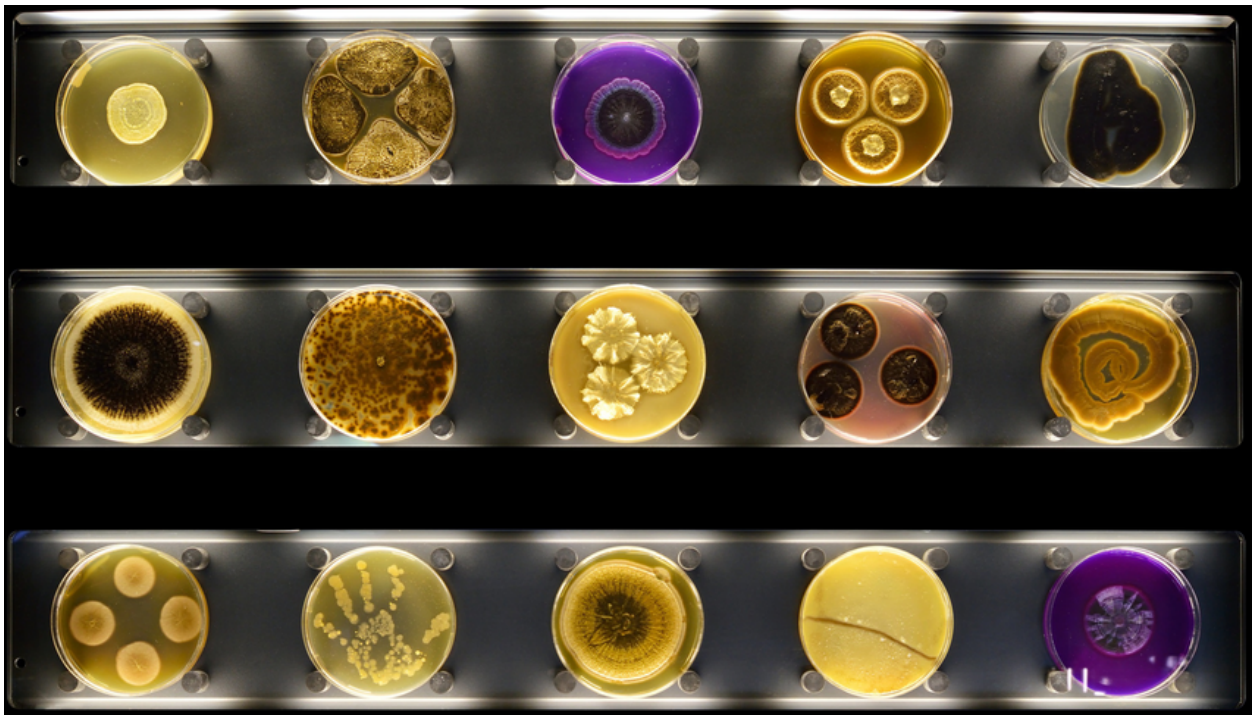

Fig. 3: Microbial art on display at ARTIS-Micropia in Amsterdam. Three rows of Petri dishes showcasing visually compelling patterns of cultured microbes. Courtesy of The Netherlands Museums Association, 2025.

under the extreme physical and chemical conditions found beyond Earth. These organisms—often called extremophiles—are adapted to extremes of temperature, pressure, radiation, salinity, and pH, and inhabit environments such as hydrothermal vents, permafrost, hypersaline lakes, and acidic waters [49]. Their survival depends on metabolisms and cellular structures evolved specifically for these extremes. Accurately simulating extraterrestrial ultraviolet (UV) radiation, which is significantly more intense and spans a wider wavelength range than the UV that reaches Earth's surface, is one of the main challenges in astromicrobiology [50]. The solar UV spectrum cannot be completely replicated on Earth even by the most powerful artificial UV generators. Nevertheless, simulation studies remain useful. As an illustration of how extremophiles might exploit the chemical environment of other planets, the acidophilic bacterium *Acidithiobacillus ferrooxidans* was found to grow successfully in simulated Martian regolith without added nutrients. In true space conditions, however, the most informative results come from orbital experiments such as the ADAPT study, which exposed genetically UV-resistant *Bacillus subtilis* spores to space radiation in Low Earth Orbit (LEO) [51]. Fig. 9 provides an overview of the interconnected medical and microbiological challenges associated with spaceflight and long-term habitation of extraterrestrial environments, illustrating how microbial survival, human health, and planetary conditions are tightly linked. This section therefore argues that microbial survival in space reshapes how we define habitability, contamination, and the origin of life.

5.1. Extremophiles Defined

Extremophiles are organisms—mostly bacteria and archaea—that not only survive but flourish in environments once thought incompatible with life. These environments include extremes of pressure, temperature, pH, radiation, salinity, and nutrient availability [52]. Extremophiles provide crucial insight into the boundaries of life on Earth and help astrobiologists evaluate the potential habitability of alien settings.

Extreme settings can be either naturally occurring or man-made; these microbes are just the result of evolution and the best adapted to their surroundings. Terms used to categorize extremophiles include: acidophiles (low pH), alkaliphiles (high pH), anaerobes (oxygen-intolerant), cryophiles/psychrophiles (cold-loving), thermophiles/hyperthermophiles (heat-loving; thermophiles $>\approx 40^{\circ}$C, hyperthermophiles $>\approx 80^{\circ}$C), piezophiles (high pressure), xerophiles (dry environments), methanogens (methane producers), and toxin-tolerant species. Examples of extreme habitats include deep-sea hydrothermal vents, ice sheets and permafrost, volcanic systems and hot springs, salt pans and hypersaline lakes, and highly acidic or alkaline waters [53, 54]. The diversity and spatial distribution of these environments are summarized in Fig. 7.

By surviving in such places, extremophiles reveal the true boundaries of Earth-based life and inform strategies for detecting life elsewhere. Extremophilic habitats can be natural (e.g., hydrothermal vents) or anthropogenic (e.g., industrial brines). Regardless of origin, extremophiles rep-

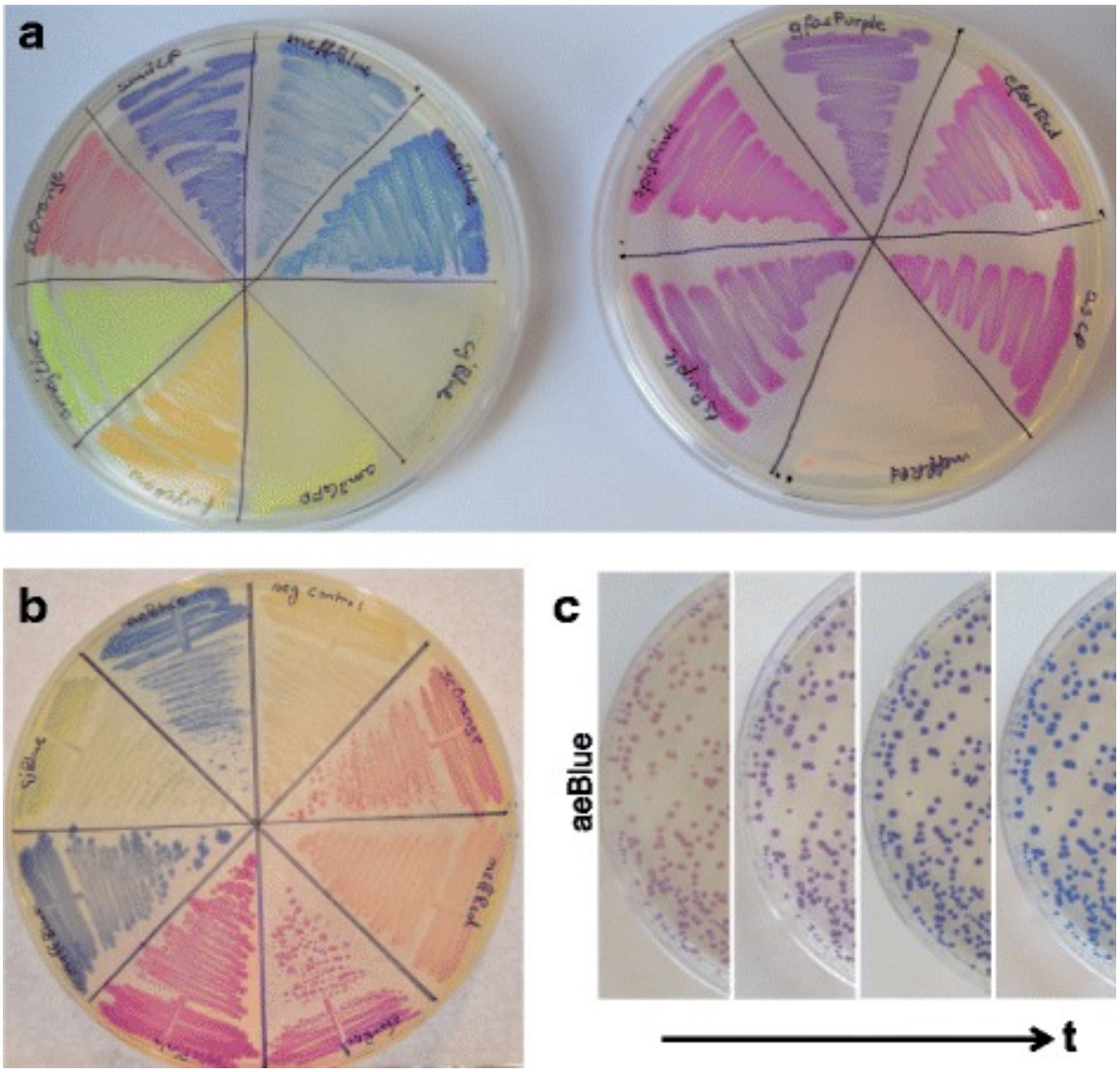

Fig. 4: Assessment of the Chromoprotein Palette. Color comparison and characterization of various eukaryotic chromoproteins (CPs) expressed in *E. coli* on agar plates. (a) Initial color comparison of 14 different CPs after 20 hours at 37°C. (b) Final color development comparison (after 4 days at 37°C) focusing on cjBlue and meffRed against a selection of CPs. (c) Time dependence of color change for aeBlue following initial 37°C incubation and subsequent 4°C storage. Reproduced from Liljeruhm J, Funk SK, Tietscher S, Edlund AD, Jamal S, Wistrand-Yuen P et al. [43].

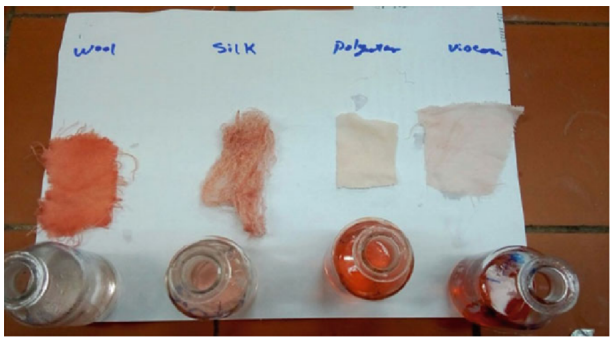

Fig. 5: Effect of red pigment produced by *Penicillium purpurogenum* application on different fabrics (wool, silk, polyester, viscose). Reproduced from Elkhateeb W, Elnahas M, Daba G [46].

resent evolution's best adaptations to particular conditions [55].

5.2. Survival on the International Space Station (ISS)

In the space experiment "Molecular adaption strategies of microorganisms to different space and planetary UV climate conditions" (ADAPT), bacterial endospores of the highly UV-resistant *Bacillus subtilis* strain MW01 were exposed for 559 days on the ESA EXPOSE-E facility mounted outside the ISS. EXPOSE-E allows biological samples to be exposed directly to space vacuum, full-spectrum solar UV radiation (>110 nm), cosmic ionizing radiation, rapid temperature cycling, and simulated Martian surface conditions [56]. The experimental configuration of the facility and the placement of ADAPT samples

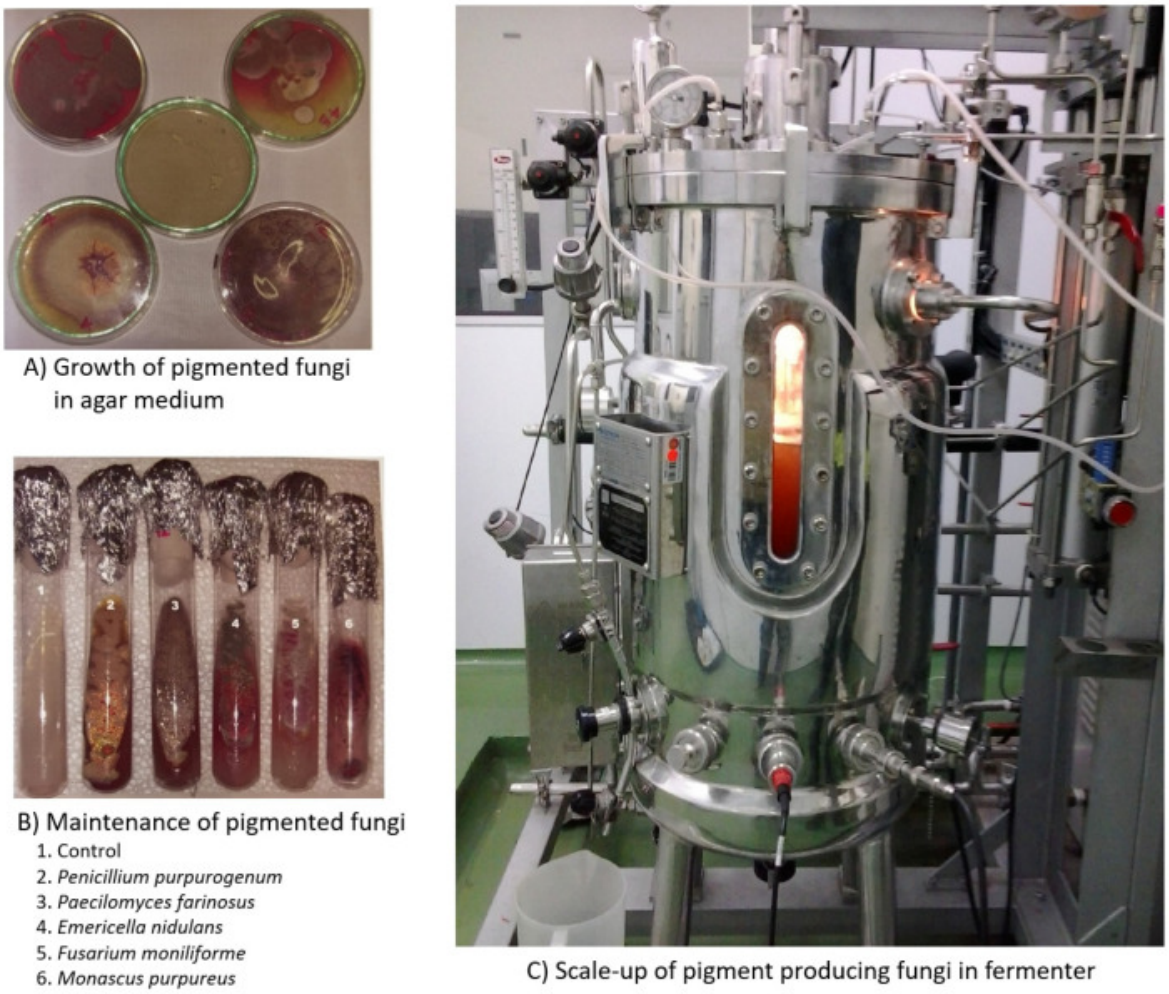

Fig. 6: Scale-up process for pigment-producing fungi from laboratory culture to industrial fermentation. The process moves from initial isolation and growth in a Petri dish to larger-scale production. (A) Growth and visualization of pigmented fungi on solid agar medium (Petri dish). (B) Maintenance and preservation of the fungal strain for long-term use. (C) Scale-up of the culture in a liquid medium within a fermenter, which is a critical step for sustainable and high-volume industrial pigment production. Reproduced from Venil CK, Velmurugan P, Dufossé L, Renuka Devi P, Veera Ravi A [48].

are shown in Fig. 10.

One main objective of Mars exploration is to detect organic compounds on the planet's surface. Therefore, understanding the preservation of organic matter under Martian-like conditions is crucial for interpreting future measurements. In ADAPT-related experiments, several organic substances (glycine, serine, phthalic acid—with and without a mineral phase—and mellitic acid) completely degraded after ~1.5 years of exposure to Mars-like UV radiation in space; under Martian surface conditions, their half-lives ranged from roughly 50 to 150 hours. Amino acids and a dipeptide, both in pure form and embedded in meteorite powder, were exposed for 18 months and then analyzed on return to Earth to study photochemical and radiolytic effects [57]. The results show that molecular structure and UV wavelength influence irradiation resistance, with alanine, valine, glycine, and aminoisobutyric acid among the more resistant compounds and others (e.g., aspartic acid) more labile. Meteorite powder provided a protective effect, highlighting the importance of mineral shielding for prebiotic organics.

5.2.1. Findings

These experiments attest to remarkable microbial resistance in LEO. *Bacillus subtilis* spores (including the UV-resistant ADAPT strain) survived ~1.5 years of exposure to vacuum, desiccation, and intense solar radiation. Some eukaryotic organisms—such as the green alga *Stichococcus* sp. and the rock-dwelling Antarctic fungus *Cryomyces antarcticus*—also survived, particularly when minimally shielded. This suggests that even thin layers of soil or rock can substantially protect organisms from space stresses, providing experimental support for lithopanspermia. In sharp contrast, many small organic molecules (e.g., glycine, serine) are highly vulnerable to photodegradation under Martian-like UV flux, which implies that absence of organ-

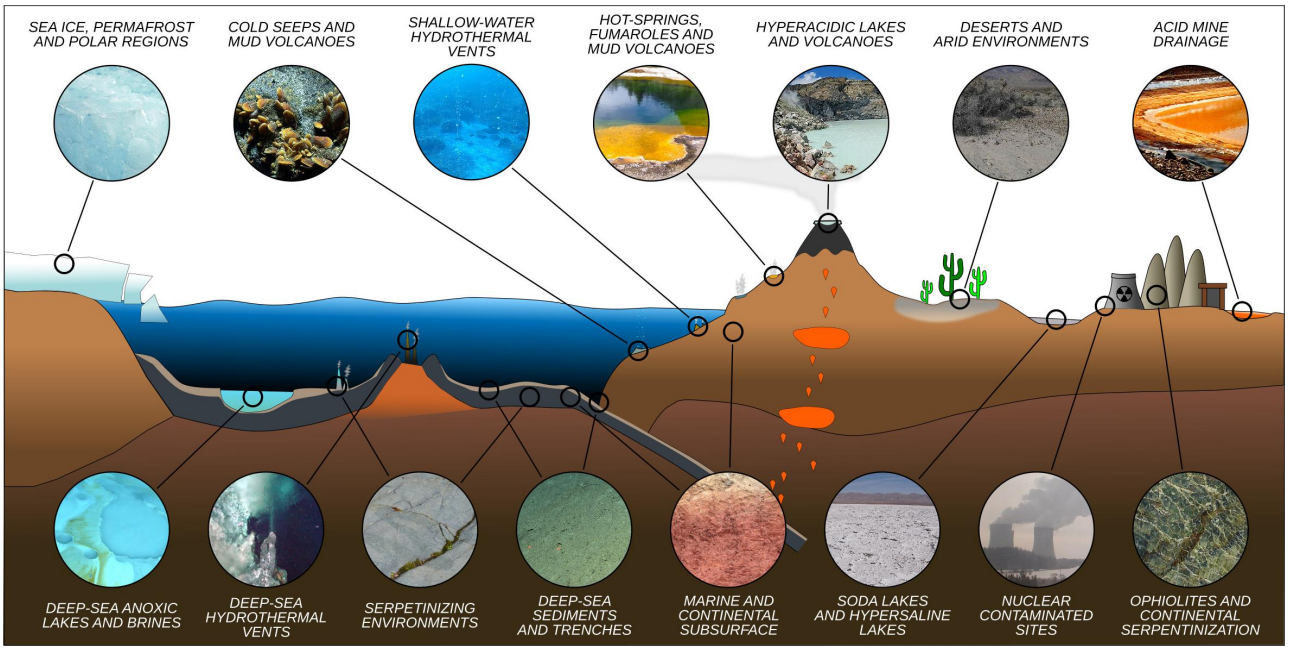

Fig. 7: Representative idealized cross section of Earth's crust showing the diversity of extreme environments and their approximate location. Reproduced from Merino N, Aronson HS, Bojanova DP, Feyhl-Buska J, Wong ML, Zhang S et al. [53].

ics on a planetary surface might reflect rapid degradation rather than absence of past biology [57].

5.2.2. Forward Contamination

EXPOSE-type experiments demonstrate that some terrestrial microbes can withstand space conditions, which raises concerns about forward contamination—the inadvertent transfer of Earth microbes to other celestial bodies via spacecraft. Highly resistant forms, such as *Bacillus* spores or cryptoendolithic fungi, can survive extreme temperatures, radiation, and vacuum, and therefore might contaminate sensitive environments on Mars, Europa, or Enceladus if transported intact [58]. Such contamination could alter native chemistries or produce false positives for life, compromising astrobiological investigations. Given that very small microbial loads can have measurable effects, missions adopt COSPAR planetary-protection protocols (sterilization, cleanroom assembly, microbial-load reduction) to preserve both scientific integrity and biological isolation of other worlds.

5.2.3. Panspermia

The demonstrated resistance of some microbes in orbital exposure tests strengthens the physical plausibility of panspermia (particularly lithopanspermia)—the hypothesis that life can be transferred between planets inside ejected rocks [59]. Although EXPOSE experiments lasted only ~1.5 years—far shorter than natural interplanetary transit times—the ability of spores, lichens, and rock-inhabiting fungi to survive vacuum, radiation, and temperature cycling shows that the biological component of interplanetary transfer can be physically possible if sufficient shielding (e.g., rock pores) exists. These experiments do not prove panspermia occurred, but they increase its feasibility by demonstrating that at least some Earth organisms possess the durability required to persist beyond the planet.

6. Conclusion

The exploration of microbial life across history, culture, and science—as documented in this paper—illuminates the multifaceted and often underestimated role of microorganisms in shaping human civilization and the cosmos. Microbes are not merely biological entities but historical agents that have driven significant societal shifts: from plagues that altered demographics and political power structures to scientific and cultural innovations that continue to influence human life. Their impact reaches beyond the laboratory—microbes have inspired artists, fueled new forms of creative expression, and challenged our understanding of life through astrobiological studies aboard the ISS. Whether thriving in the scorching heat of hydrothermal vents, frozen within polar ice, or surviving exposure to cosmic radiation, microbes continually expand the boundaries of where life can exist and how it can adapt.

Together, these examples demonstrate that microbes are powerful agents of change—shaping ecosystems, societies, and culture, and redefining the biological limits of habitability on Earth and elsewhere. Far from passive or peripheral, microorganisms drive ecological processes, inspire artistic practice, and help define the criteria we use to judge planetary habitability. In short, microorganisms are active agents woven into biological and human history.

7. Abbreviations

Abbreviation	Full Term
ADAPT	Molecular adaption strategies of microorganisms to different space and planetary UV climate conditions
COSPAR	Committee on Space Research
EXPOSE-E	European Space Agency Exposure Facility E
ISS	International Space Station
LEO	Low Earth Orbit

8. Author Contributions

- Tran Quoc Hoang: Conceived the study and developed the overall methodology (Conceptualization, Methodology). Managed the project and compiled the manuscript in Quarto (Project Administration, Software). Performed literature synthesis and wrote *Section 2* "Microbes that Changed History" and *Section 3* "Famous Microbiologists and Groundbreaking Discoveries" (Investigation, Writing – Original Draft). Contributed to reviewing and editing the manuscript (Writing – Review & Editing).
- Nguyen Hoang Tuong Vy: Wrote *Section 5* "Bacteria in Space (Astromicrobiology)" and the *Conclusion* (Writing – Original Draft). Contributed to reviewing and editing the manuscript (Writing – Review & Editing).
- Nguyen Vy Van: Wrote *Section 4* "Microbes in Art and Culture" and the *Introduction* (Writing – Original Draft). Conducted related background investigation (Investigation). Contributed to reviewing and editing the manuscript (Writing – Review & Editing).
- Nguyen Le Ngoc Vy: Co-authored the *Abstract* and summarized the manuscript to prepare presentation slides (Data Curation, Visualization). Contributed to reviewing and editing the manuscript (Writing – Review & Editing).
- Nguyen Hoang Quynh Anh: Co-authored the *Abstract* and summarized the manuscript to prepare presentation slides (Data Curation, Visualization). Contributed to reviewing and editing the manuscript (Writing – Review & Editing).

9. Declaration of Competing Interest

The authors declare no competing interests.

10. Data/Code Availability

The Quarto project underlying this paper—including the manuscript, figures, and bibliography—is available at https://github.com/ht2905/historical-microbes.

11. Appendix A: Supplementary Figures

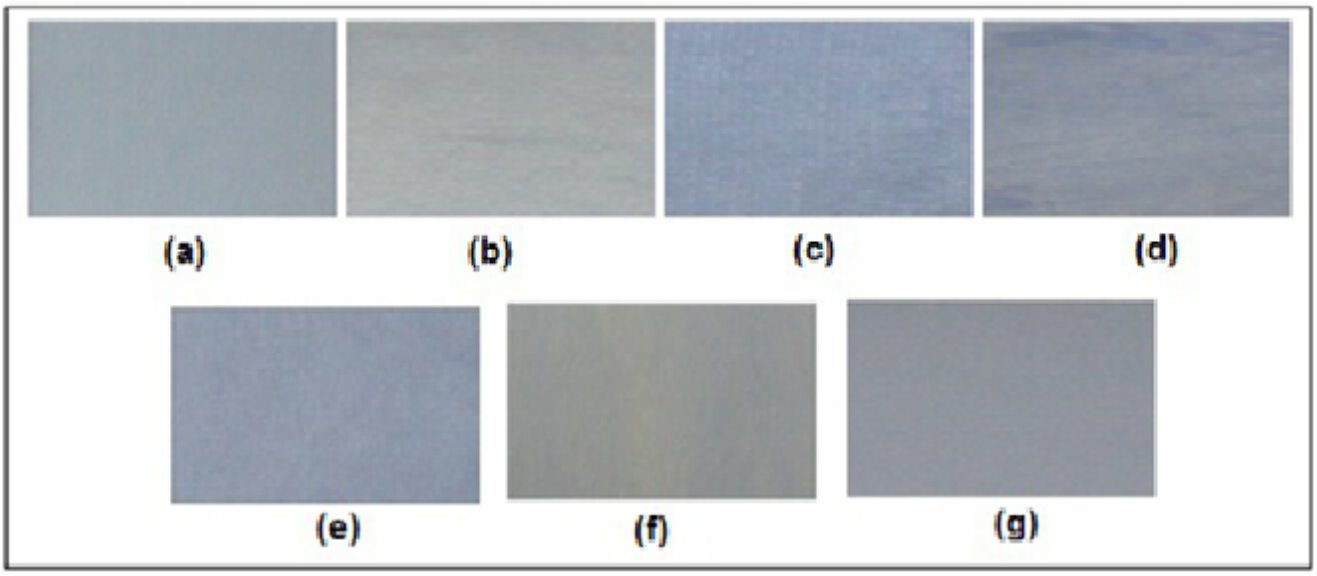

Fig. 8: Application of microbial violet pigment (violacein from *Chromobacterium violaceum*) for dyeing different textile samples, utilizing alum as the mordant. The image displays the resulting coloration on: (a) Pure cotton, (b) pure silk, (c) pure rayon, (d) rayon jacquard, (e) silk satin, (f) cotton, and (g) polyester. Reproduced from Venil CK, Velmurugan P, Dufossé L, Renuka Devi P, Veera Ravi A [39].

Table 1: List of fungal pigments produced on an industrial scale

Fungal species	**Pigments**
Monascus species	Ankaflavin (yellow), monascorubramine (red), rubropunctatin (orange)
Ophiocordyceps unilateralis	Erythrostominone (red), 3,5,8-TMON (red)
Blaskeslea tripora	β-Carotene (yellow-orange), lycopene (red)
Ashbya gossypii	Riboflavin (yellow)
Penicillium oxalicum	Anthraquinone derivative (red), anthraquinones (red and other hues)
	Arpink red^{TM}, secalonic acid D (yellow)

Note. List of fungal pigments produced on an industrial scale, synthesized from Caro Y, Venkatachalam M, Lebeau J, Fouillaud M, Dufossé L [60].

Table 2: Fungal pigments and their application in the textile industry

Fungi	**Pigment**	**Color**	**Fabrics**
Alternaria alternata	Anthraquinones	Reddish-brown	Cotton
Penicillium Oxalium	Anthraquinones	Arpink red	Wool
Chlorociboria aeruginosa	Quinones	Green	Bleached cotton, spun polyacrylic,
Scytalidium cuboideum		Red	spun polyamide, spun polyester,
Scytalidium ganodermophthorum		Yellow	worsted wool
Aspergillus sp.	Quinones	Brown cotton	Silk, silk cotton
Acrostalagmus (NRC 90)	Quinones	Brown	Wool
Alternaria alternata (NRC17)	Quinones	Reddish-brown	Wool
Alternaria sp. (NRC 97)	Quinones	Brown	Wool
Aspergillus niger (NRC 95)	Quinones	Brown	Wool
Bisporomyces sp. (NRC 63)	Quinones	Deep brown	Wool
Penicillium murcianum	Cartenoids	Yellow	Wool
Talaromyces australis	2,4-Di-tert-butylphenol	Red	Cotton fabric
Phoma harbarum	Magenta pigment	Magenta	Nylon
Talaromyces verruculosus	Polyketide	Red	Cotton fabric
Monascus purpureus	Rubropunctamine	Red	Wool

Note. Fungal pigments and their application in the textile industry. Adapted from Elkhateeb W, Elnahas M, Daba G [46].

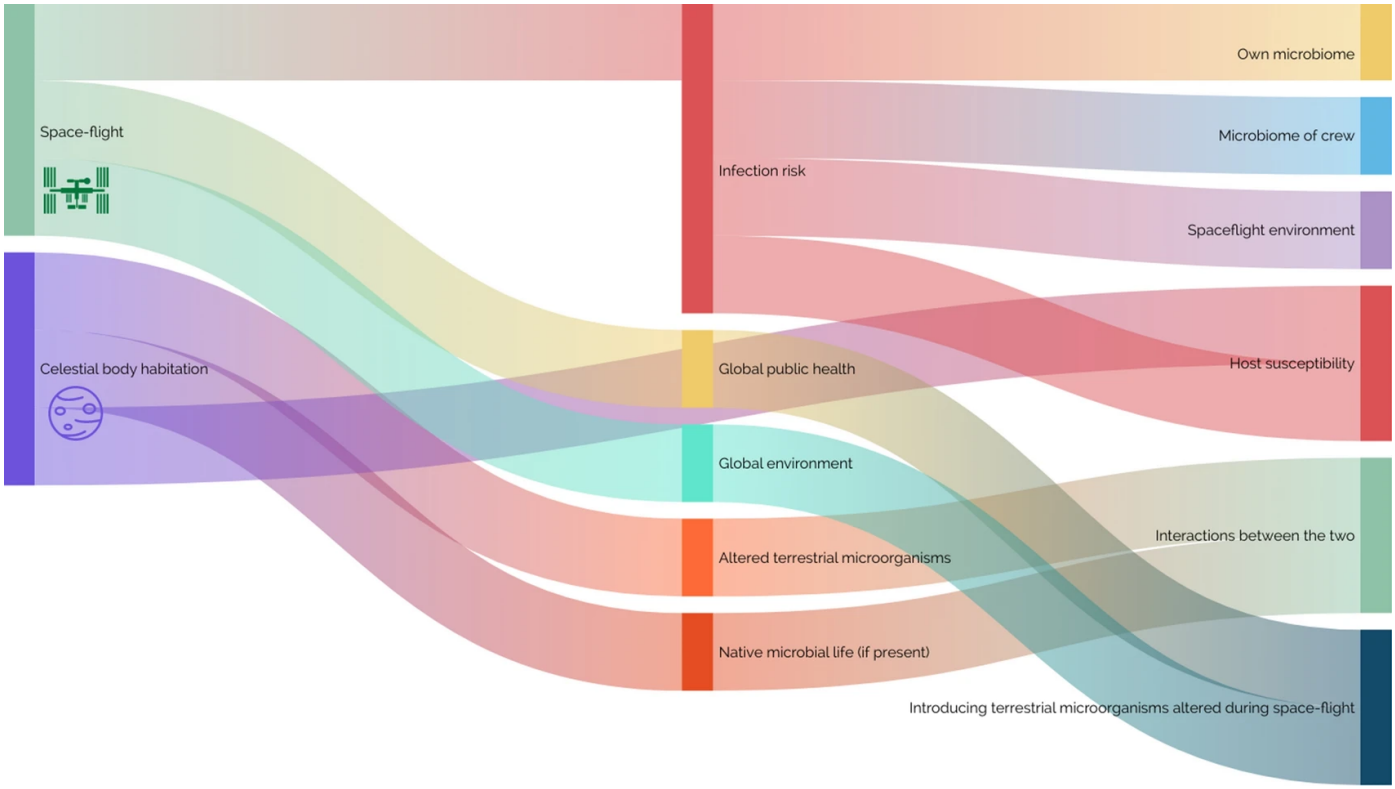

Fig. 9: A sankey diagram visualising the key medical astro-microbiology considerations relating to spaceflight and celestial body habitation. Reproduced from McDonagh F, Cormican M, Morris D, Burke L, Singh N, Venkateswaran K et al. [61].

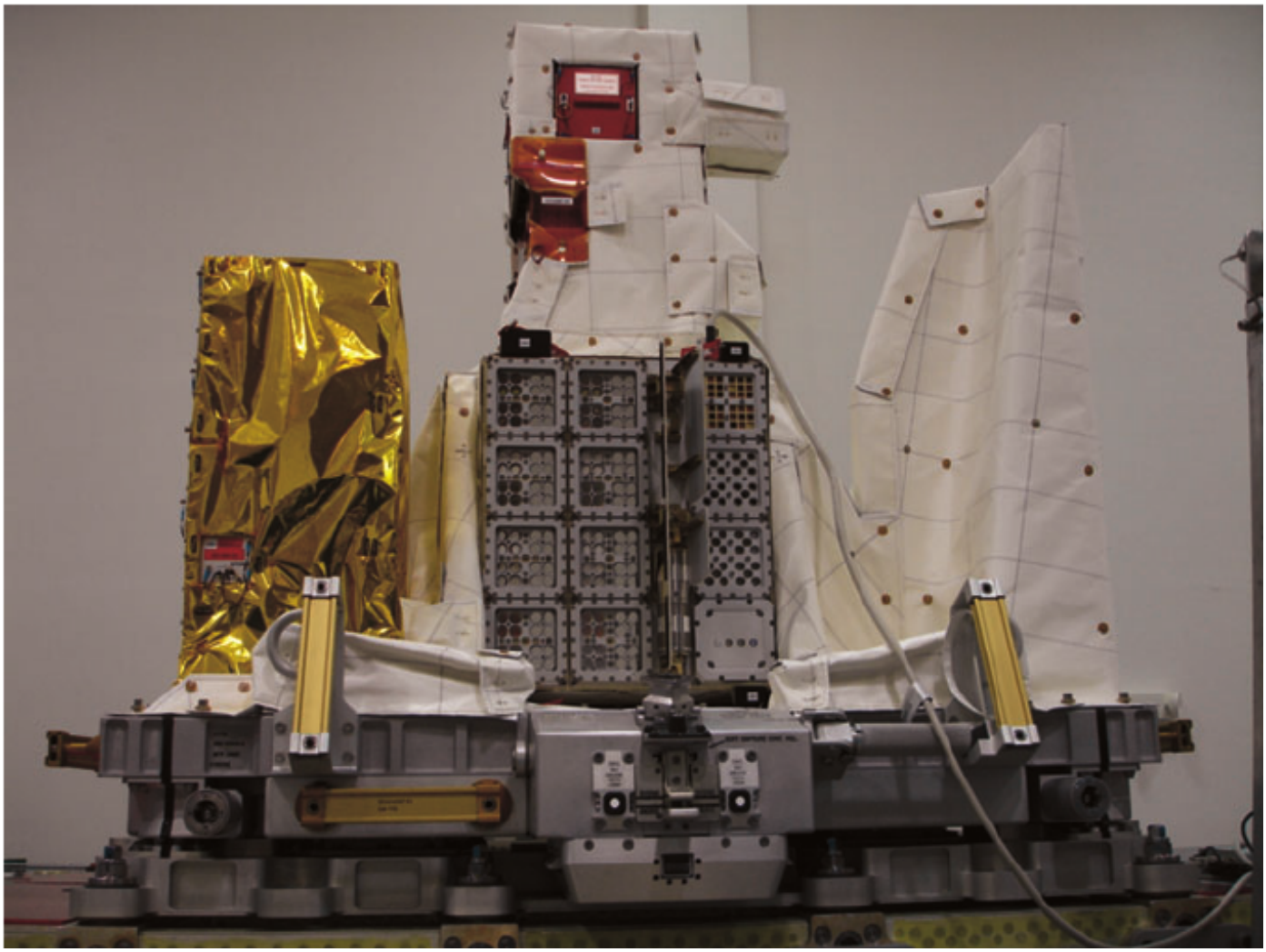

Fig. 10: EXPOSE-E payload, fully integrated and accommodated onto EuTEF at Kennedy Space Center, USA. Arranged vertically from left to right are tray 1 and tray 2—experiments in the four compartments of both trays from bottom compartment to top are ADAPT, PROTECT, $\frac{1}{2}$ ADAPT, and $\frac{1}{2}$ PROTECT sharing the third compartment and LIFE in the top compartment; on the right, separated from tray 2 by the three open lids and their motor drives, is tray 3 with R3DE in the bottom compartment, two compartments with PROCESS, and the top compartment with SEEDS. On the right half of each compartment of trays 1 and 2 the mirroring effect of the 0.1% ND filters can be seen. On the left side of EXPOSE-E, the experiment MEDET (wrapped in golden multilayer insulation) is located. Reproduced from Rabbow E, Rettberg P, Barczyk S, Bohmeier M, Parpart A, Panitz C et al. [56].

References

[1] Black Death | Plague, Death Toll, Definition, Cause, Symptoms, Effects, & Facts | Britannica, https://www.britannica.com/event/Black-Death (Nov. 2025).

[2] M. A. Spyrou, L. Musralina, G. A. Gnecchi Ruscone, A. Kocher, P.-G. Borbone, V. I. Khartanovich, A. Buzhilova, L. Djansugurova, K. I. Bos, D. Kühnert, W. Haak, P. Slavin, J. Krause, The source of the Black Death in fourteenth-century central Eurasia, Nature 606 (7915) (2022) 718–724. doi:10.1038/s41586-022-04800-3.

[3] The Black Death and European Expansion, https://www.history.ox.ac.uk/black-death-and-european-expansion.

[4] J. Aberth, From the Brink of the Apocalypse: Confronting Famine, War, Plague and Death in the Later Middle Ages, 2nd Edition, Routledge, London, 2013. doi:10.4324/9781315881133.

[5] Decameron Web | Plague, https://webhelper.brown.edu/decameron/plague/effects/social.php.

[6] Labor Shortages Alter Europe's Social Structure | Research Starters | EBSCO Research, https://www.ebsco.com/research-starters/history/labor-shortages-alter-europes-social-structure.

[7] J. J. Mark, Religious Responses to the Black Death, World History Encyclopedia (Apr. 2020).

[8] M. H. Zentner, The Black Death and Its Impact on the Church and Popular Religion.

[9] R. J. Eisen, A. P. Wilder, S. W. Bearden, J. A. Montenieri, K. L. Gage, Early-Phase Transmission of Yersinia pestis by Unblocked Xenopsylla cheopis (Siphonaptera: Pulicidae) Is as Efficient as Transmission by Blocked Fleas, J Med Entomol 44 (4) (2007) 678–682. doi:10.1093/jmedent/44.4.678.

[10] B. J. Hinnebusch, D. M. Bland, C. F. Bosio, C. O. Jarrett, Comparative Ability of Oropsylla montana and Xenopsylla cheopis Fleas to Transmit Yersinia pestis by Two Different Mechanisms, PLOS Neglected Tropical Diseases 11 (1) (2017) e0005276. doi:10.1371/journal.pntd.0005276.

[11] J. Mackay-Alderson, M. Quastel, E. Wilson, D. Bellamy, Factors influencing the re-emergence of plague in Madagascar, Emerging Topics in Life Sciences 4 (2020) 423–433. doi:10.1042/ETLS20200334.

[12] K. B. Patterson, T. Runge, Smallpox and the Native American, The American Journal of the Medical Sciences 323 (4) (2002) 216–222. doi:10.1097/00000441-200204000-00009.

[13] J. S. Marr, J. T. Cathey, New Hypothesis for Cause of Epidemic among Native Americans, New England, 1616–1619, Emerg Infect Dis 16 (2) (2010) 281–286. doi:10.3201/edi1602.090276.

[14] G. Legnaghi de Almeida, C. Santos, The microscopic settler: Smallpox dissemination in the context of european New World explorationEl colono microscópico: Diseminación de la viruela en el contexto de la exploración europea del Nuevo Mundo, Esboços: histórias em contextos globais 32 (2025) 1–22. doi:10.5007/2175-7976.2025.e101292.

[15] S. Riedel, Smallpox and biological warfare: A disease revisited, Proc (Bayl Univ Med Cent) 18 (1) (2005) 13–20. doi:10.1080/08998280.2005.11928026.

[16] N. Barquet, P. Domingo, Smallpox: The triumph over the most terrible of the ministers of death, Ann Intern Med 127 (8 Pt 1) (1997) 635–642. doi:10.7326/0003-4819-127-8_part_1-199710150-00010.

[17] P. Vaishali, N. Boopathy, Edward Jenner: The Pioneer of Vaccination and His Enduring Legacy in Modern Medicine, Cureus 16 (Sep. 2024). doi:10.7759/cureus.68805.

[18] Smallpox, https://www.who.int/health-topics/smallpox.

[19] K. A. Simonsen, J. Snowden, Smallpox, in: StatPearls, StatPearls Publishing, Treasure Island (FL), 2025.

[20] Louis Pasteur - Microbiology, Germ Theory, Pasteurization | Britannica, https://www.britannica.com/biography/Louis-Pasteur/Spontaneous-generation (Nov. 2025).

[21] Louis Pasteur and germ theory - Medicine in 18th- and 19th-century Britain, c.1700-c.1900 - Edexcel - GCSE History Revision - Edexcel, https://www.bbc.co.uk/bitesize/guides/zxbqjsg/revision/2.

[22] Pasteur-Theorie für Lebensbeginn: Stock-Vektorgrafik (Lizenzfrei) 1182778669, https://www.shutterstock.com/de/image-vector/pasteur-theory-life-beginning-1182778669.

[23] Pasteurization | Definition, Process, Inventor, & Facts | Britannica, https://www.britannica.com/technology/pasteurization (Nov. 2025).

[24] K. A. Smith, Louis Pasteur, the Father of Immunology?, Front Immunol 3 (2012) 68. doi:10.3389/fimmu.2012.00068.

[25] B. .-. A. du texte Repiquet, Méthode de M. Pasteur pour prévenir la rage après morsure, par R. Repiquet,..., 1891.

[26] R. Rappuoli, 1885, the first rabies vaccination in humans, Proceedings of the National Academy of Sciences 111 (34) (2014) 12273–12273. doi:10.1073/pnas.1414226111.

[27] R. Gaynes, The Discovery of Penicillin—New Insights After More Than 75 Years of Clinical Use, Emerg Infect Dis 23 (5) (2017) 849–853. doi:10.3201/eid2305.161556.

[28] S. Y. Tan, Y. Tatsumura, Alexander Fleming (1881–1955): Discoverer of penicillin, Singapore Med J 56 (7) (2015) 366–367. doi:10.11622/smedj.2015105.

[29] Sir Alexander Fleming – Nobel Lecture, https://www.nobelprize.org/prizes/medicine/1945/fleming/lecture/.

[30] J. A. Segre, What does it take to satisfy Koch's postulates two centuries later? Microbial genomics and Propionibacteria acnes, J Invest Dermatol 133 (9) (2013) 2141–2142. doi:10.1038/jid.2013.260.

[31] L. Walker, H. LeVine, M. Jucker, Koch's Postulates and Infectious Proteins, Acta Neuropathol 112 (1) (2006) 1–4. doi:10.1007/s00401-006-0072-x.

[32] R. Koch, Die Ätiologie der Milzbrand-Krankheit, begründet auf die Entwicklungsgeschichte des Bacillus Anthracis (Mar. 2010). doi:10.25646/5064.

[33] Ueber den augenblicklichen Stand der bakteriologischen Choleradiagnose, https://zenodo.org/records/2077681.

[34] G. K. Gesundheitsamt, Mittheilungen aus dem Kaiserlichen Gesundheitsamte: Bd. Die Aetiologie der Tuberkulose, Norddeutsche Buchdruckerei und Verlaganstalt ; zu beziehen durch Louis Gerschel Verlagsbuchhandlung (G. Gossmann), 1884.

[35] Anshi, S. Kapil, L. Goswami, V. Sharma, Anshi, S. Kapil, L. Goswami, V. Sharma, Unveiling the Intricacies of Microbial Pigments as Sustainable Alternatives to Synthetic Colorants: Recent Trends and Advancements, Micro 4 (4) (2024) 621–640. doi:10.3390/micro4040038.

[36] R. K. Suryawanshi, C. D. Patil, H. P. Borase, B. K. Salunke, S. V. Patil, Studies on production and biological potential of prodigiosin by Serratia marcescens, Appl Biochem Biotechnol 173 (5) (2014) 1209–1221. doi:10.1007/s12010-014-0921-3.

[37] D. Sangweme, E. Lampert, E. McIntosh, Microbe Art Can Educate & Correct Misconceptions about Microorganisms, The American Biology Teacher 82 (3) (2020) 162–169. doi:10.1525/abt.2020.82.3.162.

[38] S. Sulaiman, W. N. H. W. Ismail, M. I. Othman, M. N. M. Najib, IMPACT OF MICROBIAL ART ON ADVANCING STUDENTS' CULTURING PROFICIENCY IN MICROBIOLOGY EDUCATION, Asian People Journal (APJ) 6 (2) (2023) 109–118. doi:10.37231/apj.2023.6.2.548.

[39] C. K. Venil, N. Z. Yusof, C. A. Aruldass, W.-A. Ahmad, Application of violet pigment from Chromobacterium violaceum UTM5 in textile dyeing, Biologia 71 (2) (2016) 121–127. doi:10.1515/biolog-2016-0031.

[40] C. K. Venil, L. Dufossé, P. Velmurugan, M. Malathi, P. Lakshmanaperumalsamy, C. K. Venil, L. Dufossé, P. Velmurugan, M. Malathi, P. Lakshmanaperumalsamy, Extraction and Application of Pigment from Serratia marcescens SB08, an Insect Enteric Gut Bacterium, for Textile Dyeing, Textiles 1 (1) (2021) 21–36. doi:10.3390/textiles1010003.

[41] H. S. Tuli, P. Chaudhary, V. Beniwal, A. K. Sharma, Microbial pigments as natural color sources: Current trends and future perspectives, J Food Sci Technol

52 (8) (2015) 4669–4678. doi:10.1007/s13197-014-1601-6.

[42] T. Keerthana, S. S. Subhashini, Microbial Pigments: Types, Production Methods, and Diverse Applications in Various Industries: A Review, IJSAT 16 (1) (2025) 1593. doi:10.71097/IJSAT.v16.i1.1593.

[43] J. Liljeruhm, S. K. Funk, S. Tietscher, A. D. Edlund, S. Jamal, P. Wistrand-Yuen, K. Dyrhage, A. Gynnå, K. Ivermark, J. Lövgren, V. Törnblom, A. Virtanen, E. R. Lundin, E. Wistrand-Yuen, A. C. Forster, Engineering a palette of eukaryotic chromoproteins for bacterial synthetic biology, J Biol Eng 12 (2018) 8. doi:10.1186/s13036-018-0100-0.

[44] L. J. Rather, S. Jameel, S. A. Ganie, K. A. Bhat, Lichen Derived Natural Colorants: History, Extraction, and Applications, in: Handbook of Renewable Materials for Coloration and Finishing, John Wiley & Sons, Ltd, 2018, Ch. 6, pp. 103–114. doi:10.1002/9781119407850.ch6.

[45] L. Lin, J. Xu, Production of Fungal Pigments: Molecular Processes and Their Applications, J Fungi (Basel) 9 (1) (2022) 44. doi:10.3390/jof9010044.

[46] W. Elkhateeb, M. O. Elnahas, G. Daba, Wide Range Applications of Fungal Pigments in Textile Dyeing, in: T. Satyanarayana, S. K. Deshmukh (Eds.), Fungi and Fungal Products in Human Welfare and Biotechnology, Springer Nature, Singapore, 2023, pp. 289–304. doi:10.1007/978-981-19-8853-0_10.

[47] M. E. Pailliè-Jiménez, P. Stincone, A. Brandelli, Natural Pigments of Microbial Origin, Front. Sustain. Food Syst. 4 (Sep. 2020). doi:10.3389/fsufs.2020.590439.

[48] C. K. Venil, P. Velmurugan, L. Dufossé, P. Renuka Devi, A. Veera Ravi, Fungal Pigments: Potential Coloring Compounds for Wide Ranging Applications in Textile Dyeing, J Fungi (Basel) 6 (2) (2020) 68. doi:10.3390/jof6020068.

[49] M. Yokoyama, What is Astro Microbiology?, https://www.news-medical.net/life-sciences/What-is-Astro-Microbiology.aspx (Oct. 2018).

[50] G. Horneck, D. M. Klaus, R. L. Mancinelli, Space Microbiology, Microbiology and Molecular Biology Reviews 74 (1) (2010) 121–156. doi:10.1128/mmbr.00016-09.

[51] R. Moeller, P. Setlow, G. Reitz, W. L. Nicholson, Roles of small, acid-soluble spore proteins and core water content in survival of Bacillus subtilis spores exposed to environmental solar UV radiation, Appl Environ Microbiol 75 (16) (2009) 5202–5208. doi:10.1128/AEM.00789-09.

[52] G. Gallo, M. Aulitto, Advances in Extremophile Research: Biotechnological Applications through Isolation and Identification Techniques, Life (Basel) 14 (9) (2024) 1205. doi:10.3390/life14091205.

[53] N. Merino, H. S. Aronson, D. P. Bojanova, J. Feyhl-Buska, M. L. Wong, S. Zhang, D. Giovannelli, Living at the Extremes: Extremophiles and the Limits of Life in a Planetary Context, Front. Microbiol. 10 (Apr. 2019). doi:10.3389/fmicb.2019.00780.

[54] B. N. Rekadwad, W.-J. Li, J. M. Gonzalez, R. Punchappady Devasya, A. Ananthapadmanabha Bhagwath, R. Urana, K. Parwez, Extremophiles: The species that evolve and survive under hostile conditions, 3 Biotech 13 (9) (2023) 316. doi:10.1007/s13205-023-03733-6.

[55] Microbiology | Definition, History, & Microorganisms | Britannica, https://www.britannica.com/science/microbiology (Dec. 2025).

[56] E. Rabbow, P. Rettberg, S. Barczyk, M. Bohmeier, A. Parpart, C. Panitz, G. Horneck, R. von Heise-Rotenburg, T. Hoppenbrouwers, R. Willnecker, P. Baglioni, R. Demets, J. Dettmann, G. Reitz, EXPOSE-E: An ESA Astrobiology Mission 1.5 Years in Space, Astrobiology 12 (5) (2012) 374–386. doi:10.1089/ast.2011.0760.

[57] M. Wassmann, R. Moeller, E. Rabbow, C. Panitz, G. Horneck, G. Reitz, T. Douki, J. Cadet, H. Stan-Lotter, C. S. Cockell, P. Rettberg, Survival of Spores of the UV-Resistant Bacillus subtilis Strain MW01 After Exposure to Low-Earth Orbit and Simulated Martian Conditions: Data from the Space Experiment ADAPT on EXPOSE-E, Astrobiology 12 (5) (2012) 498–507. doi:10.1089/ast.2011.0772.

[58] C. Pacelli, A. Cassaro, L. Aureli, R. Moeller, A. Fujimori, S. Onofri, The Responses of the Black Fungus Cryomyces Antarcticus to High Doses of Accelerated Helium Ions Radiation within Martian Regolith Simulants and Their Relevance for Mars, Life (Basel) 10 (8) (2020) 130. doi:10.3390/life10080130.

[59] Panspermia | Research Starters | EBSCO Research, https://www.ebsco.com.

[60] Y. Caro, M. Venkatachalam, J. Lebeau, M. Fouillaud, L. Dufossé, Pigments and Colorants from Filamentous Fungi, in: Fungal Metabolites, Springer, Cham, 2015, pp. 1–70. doi:10.1007/978-3-319-19456-1_26-1.

[61] F. McDonagh, M. Cormican, D. Morris, L. Burke, N. K. Singh, K. Venkateswaran, G. Miliotis, Medical Astro-Microbiology: Current Role and Future Challenges, J Indian Inst Sci 103 (3) (2023) 771–796. doi:10.1007/s41745-023-00360-1.