

Article

Not peer-reviewed version

Living Shields: Harnessing Radiotrophic Fungal Melanin for Sustainable Lunar and Martian Habitats

[Fares Monir Akl](#) *

Posted Date: 30 January 2026

doi: 10.20944/preprints202601.2396.v1

Keywords: space architecture; fungal melanin; cosmic radiation shielding; bio-inspired design; radiotrophic fungi; extraterrestrial habitats; in-situ resource utilization (ISRU); sustainable construction



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Living Shields: Harnessing Radiotrophic Fungal Melanin for Sustainable Lunar and Martian Habitats

Fares Monir Akl

Department of Architecture, Faculty of Fine Arts, Mansoura University, Egypt; faresakl@std.mans.edu.eg

Abstract

Cosmic radiation represents a critical barrier to long-term human presence beyond Earth's magnetosphere, particularly in lunar and Martian environments [1]. Traditional shielding materials—such as regolith, water, and metallic alloys—face significant logistical, economic, and structural limitations [2]. This study investigates the potential of fungal melanin, a biological pigment known for its radiation-shielding properties in extreme environments (e.g., Chernobyl and spaceflight), as a lightweight and sustainable alternative for space architecture [3–5]. We propose an architectural framework for integrating fungal melanin into bio-inspired coatings, analyzing species-specific variations and production feasibility [6]. Comparative assessments indicate that melanin offers superior mass efficiency and architectural flexibility over conventional materials [7]. The research concludes with a roadmap for hybrid material integration and experimental validation, establishing a biologically-driven paradigm for resilient extraterrestrial habitats [8,9].

Keywords: space architecture; fungal melanin; cosmic radiation shielding; bio-inspired design; radiotrophic fungi; extraterrestrial habitats; in-situ resource utilization (ISRU); sustainable construction

1. Introduction

The primary threat to deep-space exploration is ionizing radiation, specifically Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs) [10]. The absence of significant magnetic fields or dense atmospheres on the Moon and Mars necessitates advanced shielding strategies to protect human health and structural integrity [11]. In space architecture, radiation mitigation is a fundamental design driver, dictating habitat geometry and material selection [12]. **Figure 1** illustrates the interaction between cosmic radiation and a conceptual habitat envelope.

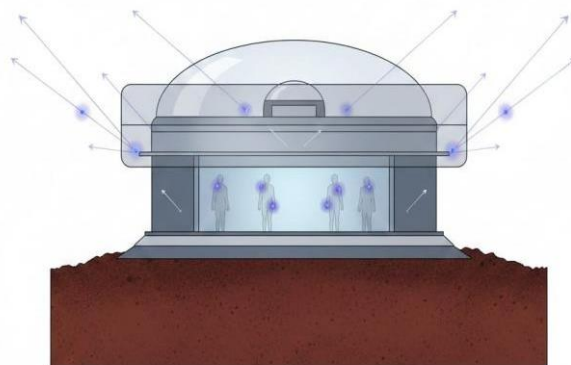


Figure 1. Cosmic radiation interaction: Fungal cells with melanin absorbing ionizing radiation.

2. Conventional Radiation Shielding Materials

Current passive shielding relies on material mass to attenuate radiation [13]:

- * Regolith: While available in-situ, it requires massive structural reinforcement and heavy excavation [14].
- * Water & Polymers: Hydrogen-rich materials are effective but present risks regarding leakage, storage, and long-term degradation [15,17].
- * Metals (e.g., Aluminum): Provide structural integrity but are prone to generating secondary radiation upon particle impact [16].

Figure 2 demonstrates conventional shielding strategies for space habitats.

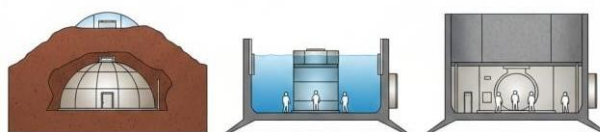


Figure 2. Conventional shielding methods: Comparison of traditional radiation shielding materials for space habitats, including regolith, water layers, and thick walls.

3. Comparative Analysis of Shielding Materials

Table 1 evaluates melanin against traditional shielding materials, highlighting its advantages in density and sustainability.

Table 1. Comparative Analysis of Space Radiation Shielding Materials.

Material	Radiation Protection Mechanism	Mass/Density Impact	Sustainability	Architectural Flexibility	Limitations	Reference
Regolith	High mass attenuation	High	Very High	Moderate	Heavy excavation, structural load	[14]
Water	Hydrogen-rich shielding	High	Medium	Low	Storage & leakage risks	[15]
Polyethylene	High hydrogen content	Medium	Medium	Medium	Degradation, aging	[15]
Aluminum	Structural shielding	Medium	Low	Medium	Secondary radiation	[16]
Fungal Melanin	Radiation absorption & interaction	Low	High	High	Requires stabilization & integration	[5,6]

This table emphasizes fungal melanin as a lightweight, sustainable, and architecturally flexible alternative.

4. Biological Responses to Ionizing Radiation

Extremophilic organisms, specifically melanized fungi, have demonstrated unique survival capabilities in high-radiation zones such as the Chernobyl exclusion zone and low-Earth orbit [18–20]. Melanin within the fungal cell wall functions as a biological shield that absorbs and dissipates ionizing energy, thereby minimizing cellular damage [21]. **Figure 3** shows melanin-rich fungal cells exposed to radiation.

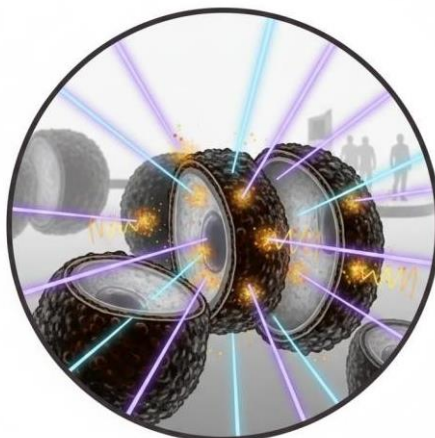


Figure 3. Melanin-rich fungal cells under radiation: Close-up of fungal cells showing melanin interacting with radiation.

5. Radiotrophic Fungi and Melanin Functionality

"Radiotrophic" fungi utilize melanin to convert radiation into metabolic energy, suggesting an active functional interaction with ionizing particles [22]. The aromatic structure of melanin allows for efficient energy dissipation, oxidative stress mitigation, and potential thermal regulation [23,24]. **Figure 4** shows radiotrophic fungi in high-radiation condi

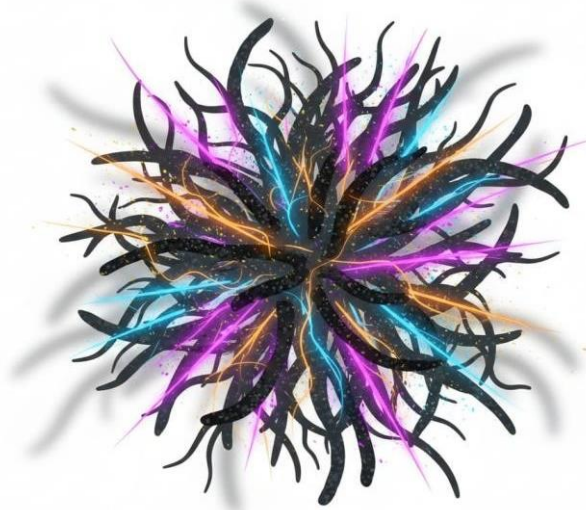


Figure 4. Radiotrophic fungi concept: Radiotrophic fungi growing in a high-radiation environment, highlighting melanin.

6. Research Gap: From Biology to Architecture

While the microbiological properties of melanin are well-documented, its application in architectural systems remains largely unexplored [25]. Current literature lacks a framework for translating these biological traits into functional coatings or composite materials suitable for large-scale space construction [26,27]. **Figure 5** visualizes the research gap between biology and architectural applications.

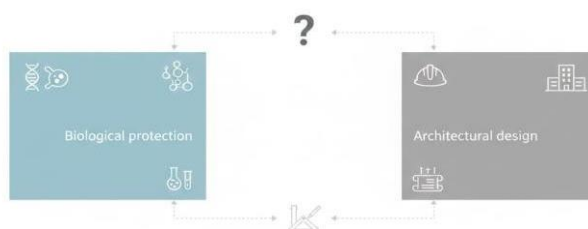


Figure 5. Research gap diagram: Gap between biological radiation protection studies and space.

7. Proposed Concept: Melanin-Based Architectural Coatings

This research proposes the development of melanin-derived bio-coatings for habitat envelopes [28]. Produced terrestrially or via bio-reactors, these coatings can be stabilized and applied as a passive radiation layer [29]. This approach is designed to be synergistic, augmenting existing regolith or structural systems to provide a multi-layered defense [30]. **Figure 6** depicts a conceptual melanin-based coating applied to a space habitat envelope.



Figure 6. Melanin-based coating on habitat envelope: Space habitat section showing a melanin coating absorbing radiation.

8. Architectural Implications

Melanin-based coatings facilitate the design of lightweight, adaptive space habitats [31]. Beyond radiation protection, these coatings enhance thermal regulation and material durability, reducing the mass-to-orbit requirements for protective structures [32]. **Figure 7** illustrates bio-inspired adaptive space architecture integrating melanin-based coatings.



Figure 7. Adaptive bio-inspired space habitat concept: Futuristic space habitat with adaptive envelope inspired by biological materials.

9. Challenges and Future Research Directions

Implementation requires addressing the following challenges [33]:

- * Stability: Behavior under vacuum and extreme thermal cycling.
- * Scalability: Optimization of large-scale melanin synthesis.
- * Hybridization: Integrating melanin with polymeric composites or regolith.
- * Validation: Testing under simulated Martian/Lunar radiation conditions.

Figure 8 projects potential bio-integrated space habitats leveraging melanin-based coatings.



Figure 8. Future bio-integrated habitats: Future space habitats using bio-grown materials and living coatings for radiation protection.

10. Conclusion and Recommendations

Fungal melanin provides a sustainable, bio-inspired pathway for radiation shielding in space [34]. By bridging biological resilience with architectural material science, melanin-based coatings offer significant reductions in structural mass and enhanced multifunctional protection [35].

Recommendations:

- * Initiate in-situ testing under simulated extraterrestrial radiation.
- * Develop hybrid melanin-PLA or melanin-regolith composite systems.

- * Tailor species-specific melanin types for diverse environmental stressors.
- * Integrate coatings into modular habitat designs for flexible architecture.

References

1. National Research Council. (2008). *Managing Space Radiation Risks in the New Era of Space Exploration*. National Academies Press.
2. Spill Antini, P., et al. (2007). Shielding from cosmic radiation for interplanetary missions. *Radiation Measurements*.
3. Dadachova, E., & Casadevall, A. (2008). Ionizing radiation: how fungi cope, adapt, and exploit with the help of melanin. *Current Opinion in Microbiology*.
4. Zhdanova, N. N., et al. (2000). Ionizing radiation resistance of fungi from the Chernobyl reactor. *Mycological Research*.
5. Dadachova, E., et al. (2007). Ionizing Radiation Changes the Electronic Properties of Melanin and Enhances the Growth of Melanized Fungi. *PLoS ONE*.
6. Cordero, R. J., et al. (2017). Melanin-based fertilizers as a potential strategy for space agriculture. *Life Sciences in Space Research*.
7. Shunkov, V., et al. (2020). Evaluation of the shielding properties of fungal melanin against ionizing radiation. *Materials Science and Engineering*.
8. Rothschild, L. J. (2016). *Synthetic Biology: The Best Way to Live off the Land in Space*. AIAA SPACE.
9. Averagesch, N. J. H., et al. (2020). A Biological Solution to Radiation Shielding on the Moon. *Life*.
10. Durante, M., & Cucinotta, F. A. (2011). Physical basis of radiation protection in space travel. *Reviews of Modern Physics*.
11. Simonsen, L. C., et al. (2020). NASA's Artemis program: Space radiation risks and protection. *Journal of Space Safety Engineering*.
12. Howe, A. S., et al. (2013). Radiation shielding for a lunar habitat. *Journal of Aerospace Engineering*.
13. Cucinotta, F. A., et al. (2013). Space radiation cancer risk projections for exploration missions. *NASA/TP*.
14. Benaroya, H. (2018). *Building Habitats on the Moon*. Springer Praxis Books.
15. Zeitlin, C., et al. (2013). Measurements of energetic particle radiation in transit to Mars on the MSL. *Science*.
16. Wilson, J. W., et al. (1995). Shielding from solar particle events: optimized configurations. *Health Physics*.
17. Kim, M. Y., et al. (2006). Comparison of multi-layer shielding materials for space radiation. *Radiation Measurements*.
18. Tugay, T., et al. (2006). The influence of ionizing radiation on spore germination and emergent hyphal growth of fungi from Chernobyl. *Mycological Research*.
19. Romsos, C., & Romsos, J. (2020). Radiotrophic Fungi on the International Space Station. *Astrobiology Journal*.
20. Shcherbakov, S. V., et al. (2021). Fungal growth under high radiation environments: from Chernobyl to Orbit. *International Journal of Astrobiology*.
21. Schweitzer, A. D., et al. (2009). Melanin-covered nanoparticles for protection of bone marrow during radiation therapy. *International Journal of Radiation Oncology*.
22. Robertson, K. L., et al. (2012). Adaptation of Fungi to Ionizing Radiation in a Low-Nutrient Environment. *Applied and Environmental Microbiology*.
23. Meredith, P., & Sarna, T. (2006). The physical and chemical properties of eumelanin. *Pigment Cell Research*.
24. Solano, F. (2014). Melanin: A Long-Lasting History with Some Recent Breakthroughs. *International Journal of Molecular Sciences*.
25. Imhof, B., et al. (2017). Biologically inspired space architecture. *Acta Astronautica*.
26. Armstrong, R. (2015). *Vibrant Architecture: Matter as a Co-designer of Living Structures*. De Gruyter.
27. Mohanty, S. (2021). The potential of biomaterials in extraterrestrial habitat construction. *Space Policy*.
28. Senst, N., et al. (2021). Microbial production of melanin for radiation shielding applications. *Frontiers in Bioengineering and Biotechnology*.

29. Goshu, G. M., et al. (2021). Stabilization of fungal melanin in polymer composites for space applications. *Materials Letters*.
30. Montalbán, M. G., et al. (2022). Synergistic effects of regolith-melanin composites for Mars shielding. *Advanced Space Research*.
31. Sherwood, B. (2019). *Principles for Human Lunar Architecture*. New Space.
32. Cohen, M. M. (2002). The aesthetics of space architecture. *AIAA Space Conference*.
33. Korthals Altes, S. (2020). Engineering Challenges for Living Materials in Extreme Environments. *Journal of Biotechnology*.
34. Shrestha, R. K., et al. (2021). Fungal biomaterials: A sustainable future for space habitats. *Biomaterials Science*.
35. NASA Technology Roadmaps. (2020). TA 06: Human Health, Life Support, and Habitation Systems.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.