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Astrobiomineralogy: A Systematic Review of Mineral-Microbe Interactions and Biosignatures in Extreme and Extraterrestrial Environments

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INTRODUCTION & AIM

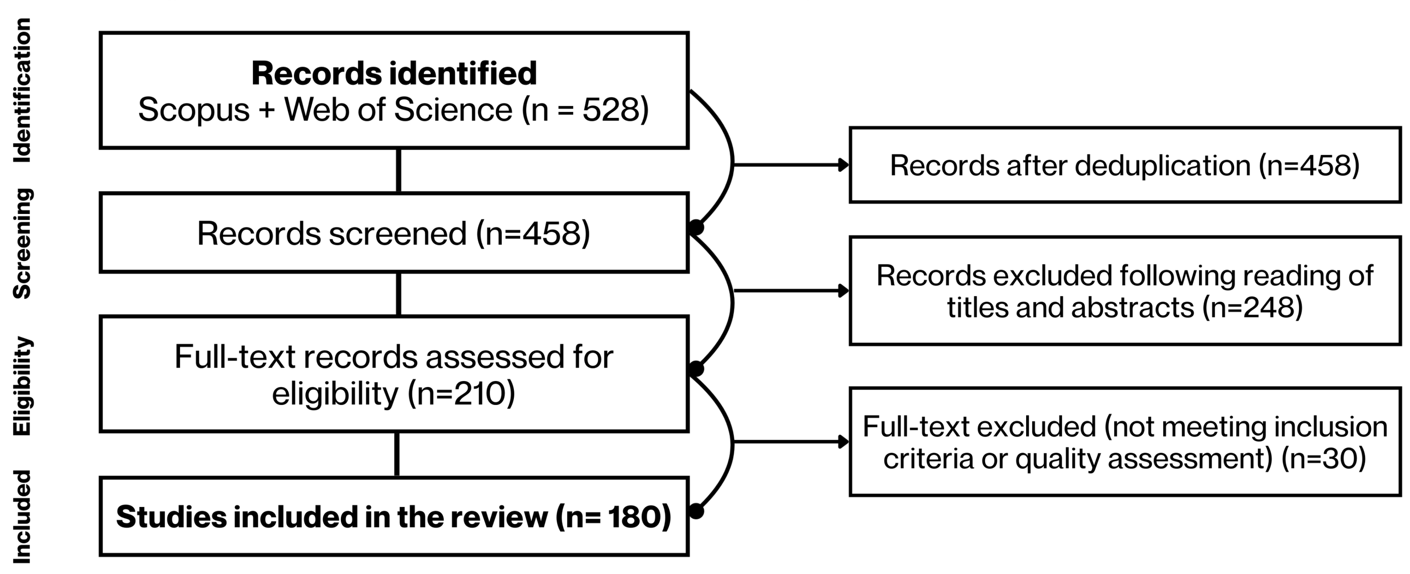
Astrobiomineralogy integrates mineral science, microbiology, planetary geology, and space biomedicine by recognizing minerals as active agents that shape habitability and biological persistence. Through catalytic reactivity, nutrient cycling, microhabitat formation, radiation shielding, and long-term preservation of biosignatures, mineral–microbe interactions operate across scales, from nanoscale surface processes to mineral assemblages detectable by in situ and laboratory-based techniques.

Terrestrial extreme environments, such as hyperarid, saline, irradiated, and cryogenic systems, serve as key analogues for extraterrestrial settings. In these environments, minerals including sulfates, phyllosilicates, and iron oxides support extremophilic life and generate mineralogical features that overlap with biosignatures sought on Mars and icy moons. The growing use of Raman and X-ray-based instruments in planetary exploration underscores the need for robust mineralogical frameworks, while insights from astrobiomineralogy also inform space biomedicine by addressing radiation exposure, mineral dust hazards, and mineral–microbe technologies relevant to long-duration human spaceflight.

METHOD

This study was conducted as a systematic review following the PRISMA guidelines, ensuring transparency, reproducibility, and alignment with international standards for evidence synthesis in mineral sciences and astrobiology (Figure 1).

Figure 1. PRISMA flow diagram summarizing the literature selection process.

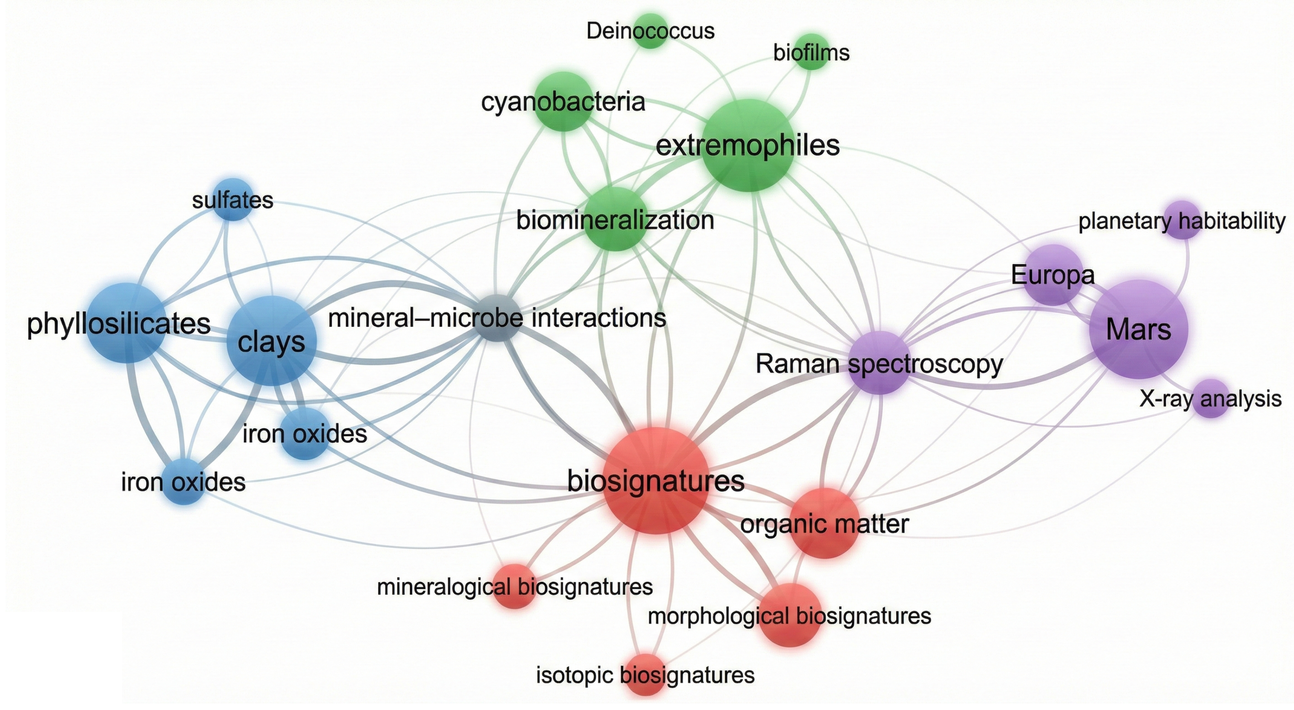


Peer-reviewed articles published between 2010 and 2025 were included if they addressed mineral–microbe interactions, biomineralization, or biosignatures in extreme terrestrial or simulated extraterrestrial environments and contained a clear mineralogical component. Studies lacking mineral context, non-peer-reviewed materials, and purely theoretical works were excluded.

Literature searches were performed in the Scopus and Web of Science databases using combined biological, mineralogical, environmental, and detection-related keywords, with filters applied for English language and publication year. Search terms targeted extremophiles, key mineral substrates (e.g., clays, sulfates, iron oxides), planetary analogues, and biosignature detection techniques.

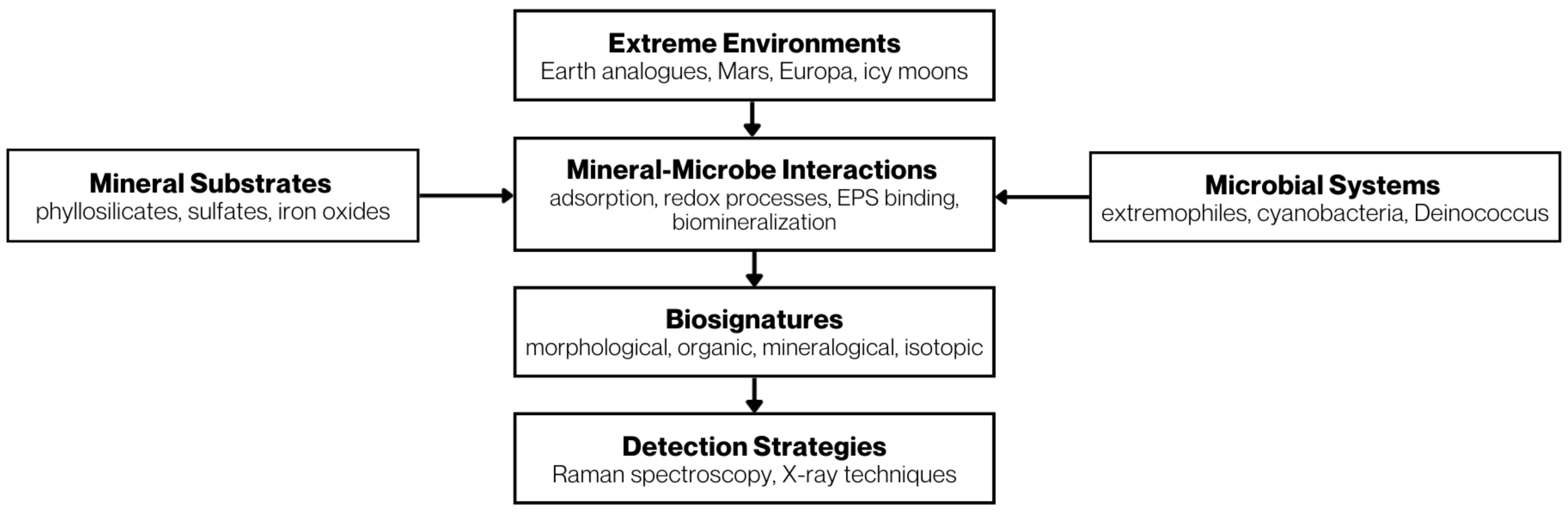
Study selection involved deduplication, title and abstract screening, and full-text eligibility assessment, yielding 180 studies from 528 records, as summarized in the PRISMA flow diagram (Figure 1). Data extraction covered environment type, microbial taxa, mineral substrates, interaction mechanisms, biosignature classes, and analytical methods. Bibliometric and co-word analyses were performed using VOSviewer to identify thematic clusters and research trends (Figure 2)

Figure 2. Co-word network analysis generated using VOSviewer, highlighting major thematic clusters and research trends related to mineral substrates, microbial processes, biosignatures, and planetary exploration.



RESULTS & DISCUSSION

Figure 3. Conceptual framework of mineral–microbe interactions and biosignature formation in extreme and extraterrestrial environments.



Across the 180 studies analyzed, three convergent patterns emerged: recurrent associations between extremophiles and key mineral substrates (phyllosilicates, sulfates, and iron oxides); a strong dependence of biosignature detectability on analytical techniques, particularly Raman and X-ray–based methods; and **increasing translation of terrestrial analogue studies to Mars and icy-moon contexts.** These relationships are synthesized in Figure 3, while the main mineral substrates and biosignature relevance are summarized in Table 1.

Mineral substrate	Main interaction	Biosignature relevance	Key detection
Phyllosilicates (clays)	Organic adsorption, EPS binding, surface catalysis	High preservation of organics and microtextures	**Raman, XRD**
Sulfates (evaporites)	Crystal entombment, sulfate precipitation	Pigments and crystal-hosted biosignatures	**Raman**, microscopy
Iron oxides	Redox cycling, mineral coatings	Durable mineralogical biosignatures	**Raman, XRF**

Table 1. Key mineral substrates, dominant microbe–mineral interactions and biosignature relevance in extreme environments.

Phyllosilicates (clays) stand out as prime habitability indicators and preservation media due to their layered structures, high surface area, and cation-exchange capacity, favoring organic adsorption, EPS-mediated biofilms, and microtexture stabilization.

Sulfates and evaporites, common in hyperarid and saline environments on Earth and Mars, can entomb organic matter and biomolecules within crystals or pore networks, although high ionic strength and low water activity strongly constrain microbial survival.

Iron oxides play a key role in redox-driven mineral–microbe interactions, acting as energy substrates and forming durable mineralogical products capable of retaining biosignatures under harsh conditions.

Among microbial models, cyanobacteria and *Deinococcus* spp. dominate analogue studies, contributing biofilms, laminated textures, pigments, and extreme resistance to radiation and desiccation. Overall, reported biosignatures include morphological, molecular/organic, and mineralogical classes, highlighting the need for a multi-proxy approach that integrates mineralogical context and complementary detection methods in planetary exploration.

CONCLUSION

This review demonstrates that minerals function as active ecological and preservational agents in extreme environments, linking extremophiles, especially cyanobacteria and *Deinococcus* spp., to sulfates, phyllosilicates, and iron oxides also found on Mars and icy moons. Raman and X-ray techniques emerge as key tools for detecting durable mineral-hosted biosignatures, highlighting the relevance of astrobiomineralogy for planetary exploration and space biomedicine under radiation, desiccation, and low-gravity conditions.

FUTURE WORK

Build standardized spectral libraries (mineral-organic mixtures) under radiation/desiccation conditions; Integrate lab simulations with rover-scale constraints (sampling depth, fluorescence, matrix effects); Translate mineral-microbe insights to space health: dust reactivity, bio-shielding, bio-resource utilization.