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From Rock to Soil: Biomimetic and Ontological Reflections on Substrate Transformation for Sustainable Systems

Ille C. Gebeshuber, Institute of Applied Physics, TU Wien, Austria

gebeshuber@iap.tuwien.ac.at

How does life make the uninhabitable habitable? How can rock become soil – in alpine debris fields, in karstic deserts or even on other celestial bodies?

This contribution explores the emergence of living soil from lifeless stone as a process of biological ingenuity and systemic interaction. It draws on current biomimetic research and philosophical inquiry to propose a set of general principles for sustainable transformation of marginal environments. The mechanisms by which alpine pioneer plants, microbial consortia and fungi create structure, stability and fertility in unstable, nutrient-poor substrates are interpreted as ontological acts of becoming: rock is not a passive object, but a potentiality activated through biotic relation.

In natural systems, plants do not wait for soil – they make it. Through the release of root exudates (e.g., oxalic and citric acid), they mobilize minerals from solid rock. In collaboration with microbial partners (e.g., nitrogen-fixing bacteria, mycorrhizal fungi), they stabilize loose debris through biofilms, exopolysaccharides and hyphal networks. These biological interfaces create conditions for water retention, nutrient cycling and long-term habitability. Such microscale interactions eventually scale up to ecological systems – a process with profound implications for ontological modelling, sustainability science and future technologies.

In particular, mosses and lichens act as primary biotic rock formers. Lichens produce organic acids that chemically weather mineral surfaces, while their tightly adhering growth forms introduce mechanical stress via cycles of hydration and desiccation. Mosses trap dust, spores and organic particles, contributing to the very first organic-mineral interface. Together, they create early microhabitats that harbour microbes, cyanobacteria and algae, thus initiating the first steps toward biogenic soil. These cryptogamic pioneers illustrate that colonization, not conquest, lies at the root of transformation – a lesson relevant far beyond ecology.

From a biomimetic perspective, these processes can be translated into design principles such as: (1) cooperation as a generative force, (2) structural stabilization through soft connectivity, (3) resource availability through chemical signalling and (4) slowness as a strategy for resilience. Such principles are directly relevant for sustainable material development, regenerative agriculture and circular approaches to food and waste systems – especially in marginal or degraded environments.

In the context of waste ontologies, these insights offer a new lens: instead of asking how to eliminate waste, we ask how waste can become the foundation for regenerative systems – just as rock becomes soil. Organic and inorganic residues (such as degraded bioplastics or construction debris) might be re-integrated into living systems through biological mineralization, microbial colonization or structural embedding. In this light, waste is not absence of value but precondition of process.

We further propose a biomimetically informed ontology of becoming, where entities are not fixed substances but relational fields. Soil is not merely a container of nutrients, but an emergent effect of interaction. Waste is not merely discarded matter, but suspended potential. Sustainability, then, is not a static goal, but an ongoing dialogue between systems and substrates.

Drawing inspiration from our recent publication on the “good enough” principle in *Advanced Functional Materials*, we argue for a shift from high-performance optimization toward context-responsive sufficiency – mimicking natural systems that are robust, flexible and adaptive rather than maximized.

Finally, we discuss ethical dimensions of such biomimetic applications in extraterrestrial settings. Planetary protection protocols prohibit uncontrolled biological introduction to the Moon or Mars, yet Earth-based simulations show promising results with microbial and plant-based Regolith processing. (Regolith is everything loose and unconsolidated on top of solid rock, whether on Earth, the Moon, Mars or asteroids.) These findings reinforce the responsibility to learn from extreme environments on Earth – such as karst landscapes and deserts – before exporting our life-making strategies into space.

In summary, this contribution offers a multi-level reflection – from molecular processes to philosophical principles – on how life creates fertile systems from inert material. It invites participants to integrate biomimetic insight, sustainability modelling and ontological frameworks into a unified understanding of transformation, waste and planetary care.

References

1. van Nieuwenhoven, R. W., Drack, M., & Gebeshuber, I. C. (2023). *Engineered Materials: Bioinspired “Good Enough” versus Maximized Performance*. **Advanced Functional Materials**, 34(35), 2307127. https://doi.org/10.1002/adfm.202307127
2. Hinsinger, P. (2001). *Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review*. **Plant and Soil**, 237(2), 173–195.

3. Sheldrake, M. (2020). *Entangled Life: How Fungi Make Our Worlds, Change Our Minds and Shape Our Futures*. Random House.
4. Wamelink, G. W. W., Frissel, J. Y., et al. (2014). *Can plants grow on Mars and the Moon: a growth experiment on Mars and Moon soil simulants*. **PLOS ONE**, 9(8), e103138.
5. Chen, J., Blume, H.-P., & Beyer, L. (2000). *Weathering of rocks induced by lichen colonization – a review*. **Catena**, 39(2), 121–146.
6. Gadd, G. M. (2007). *Geomycology: biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, bioweathering and bioremediation*. **Mycological Research**, 111(1), 3–49.
7. Ehrenfreund, P., Race, M., & Labdon, D. (2013). *Responsible space exploration and use: Balancing stakeholder interests*. **New Space**, 1(2), 60-72.