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Fractal Architecture as a Foundational Design Principle in Biomimetic Material Engineering

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Introduction

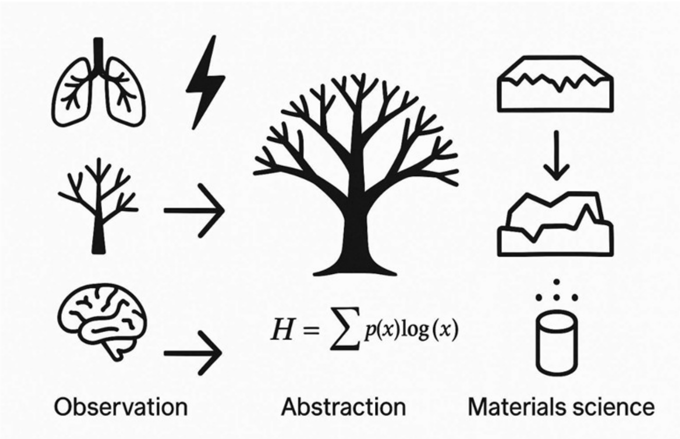

Figure 1. Figure caption

Biomimetics often replicates biological forms, but the structural principles behind efficiency, resilience, and scalability are less explored.

Reviewing ~200 studies on nanowires, catalysts, electrodes, and porous materials revealed a recurring feature: **fractal architecture**.

Fractals—self-similar and scale-invariant—maximize surface area, distribute stress, and optimize transport. Two optimal fractal dimension ranges emerged: **1.6–1.8** (nanostructures) [1] and **2.4–2.6** (bulk porous systems) [2], reflecting trade-offs between robustness and efficiency.
This work reframes fractality as a **universal design principle** linking materials science, biology, and engineering for scalable, high-performance systems.

Methods

This literature review analyzed peer-reviewed studies on fractal architecture in biomimetic materials engineering, sourced from Google Scholar, PubMed, and Web of Science.

Using keywords such as **fractal dimension, scale-free network, and biomimetics**, relevant works were synthesized into a framework linking fractal geometry to mechanical, electrical, and multifunctional properties.

Key Findings

- Deviations from D_opt—either lower (simpler) or higher (more complex) structures—reduce performance and increase fragility.
- Theoretical modeling aligns with empirical evidence from biological and engineered systems, suggesting broad applicability in biomimetic design.

Results

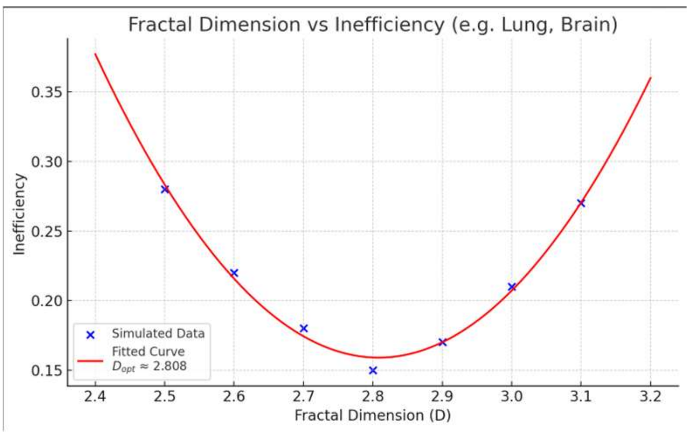

Figure 2. Hypothetical example illustrating the concept of an optimal fractal dimension (D_{opt})

Analysis of peer-reviewed studies revealed that many biological and engineered systems operate most efficiently near a specific fractal dimension. Significant deviation—toward overly simple or overly complex architectures—correlates with reduced performance, higher resource use, and structural fragility.

$$f(D) = a*(D - D\_opt)^2 + C$$

A simulated model with hypothetical lung and brain data showed a distinct efficiency peak at **D_opt ≈ 2.8D**, where inefficiency is minimal. Moving away from this value in either direction led to measurable decline.

Empirical evidence supports this trend: **in conditions such as schizophrenia, cardiovascular disease, and emphysema, optimized fractal structures degrade, aligning with the prediction that deviation from the optimal dimension harms stability and function**. This convergence of theory and observation highlights the potential universality of the optimal fractal dimension principle for biomimetic design.

References

[1] Nicolás-Carlock, J.R., Carrillo-Estrada, J.L. & Dossetti, V. Universal fractality of morphological transitions in stochastic growth processes. *Sci Rep* **7**, 3523 (2017). https://doi.org/10.1038/s41598-017-03491-5
[2] Zuo, Y.-T. & Liu, H.-J. Fractal approach to mechanical and electrical properties of graphene/SiC composites. *Facta Universitatis, Series: Mechanical Engineering* **19**(2), 271–284 (2021). https://doi.org/10.22190/FUME201212003Z
[3] Cha, J., DeDora, D., Nedic, S., Ide, J., Greenberg, T., Hajcak, G., & Mujica-Parodi, L.R. Journal of Neuroscience, 36(17), 4708–4718 (2016). https://doi.org/10.1523/JNEUROSCI.1092-15.2016

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