

CHEMISTRY

Mineral Crystal Assembly at Room Temperature and Ambient Pressure

How biology builds hard materials without kilns or high pressure

5	3	1–3	5
convergent strategies	principle clusters	TRL range	featured strategies

PROBLEM FRAMING

Conventional ceramic manufacture requires temperatures of 1,000–1,600°C and high pressure. Marine organisms — molluscs, sea urchins, corals — build mechanically superior mineral structures at ambient temperature, in seawater, using protein templates and enzymatic catalysis.

Application domains: materials, medicine, architecture

Principle cluster: biomineralization, self organization, enzymatic catalysis

Physics & Mechanism

Underlying physics

[DRAFT] Biological mineralisation is templated nucleation: acidic glycoproteins adsorb on a pre-formed organic matrix and selectively stabilise specific crystal faces, directing polymorph selection and crystal orientation. Nacre forms from amorphous calcium carbonate (ACC) precursor — metastable, soluble, easily transportable — that transforms to aragonite (the thermodynamically stable form under biological conditions) at the organic matrix surface. The matrix proteins select aragonite over calcite by stabilising the (001) aragonite face. Sea urchin larval spicule forms as a single calcite crystal with magnesium substitution (up to 15 mol% MgCO_3) that increases hardness while maintaining optical transparency over the relevant crystallographic axis. Bone hydroxyapatite forms via non-classical nucleation: calcium phosphate clusters (~1 nm) nucleate within the hole zones of collagen fibrils (gap between collagen molecules, 67 nm repeat), oriented with the c-axis parallel to the fibril. Engineering pathways: recombinant protein templates, silica-based mineralisation (silicateins), and polyelectrolyte multilayer templates. Room-temperature ceramics via biology-inspired approaches are advancing rapidly for biomedical implants. [END DRAFT]

Biological Strategies

Chemically Assemble Mineral Crystals Sponges

Sponges construct their skeletal silica structures via enzymatic catalysis mediated by silicatein, a protein that facilitates the hydrolysis and condensation of silica precursor molecules. That process occurs under mild aqueous conditions at ambient temperature, allowing the organism to build complex three-dimensional mineral architectures with precise control. This silicatein protein acts as a bi...

Design principle: Engineers can replicate sponge silica synthesis by designing synthetic peptides that mimic silicatein's catalytic properties. Block copolypeptides containing cysteine and lysine residues can self-orga

Chemically Assemble Mineral Crystals Leafcutter ant · TRL 3/9 · 33 genera ♦ Evidence File

Atta cephalotes, the leafcutter ant, constructs mineralized composite materials by combining biological catalysis with structural scaffolding. The ant uses enzyme-induced mineralization to transform soft, flexible hydrogel matrices into rigid, densely mineralized composites. In laboratory biomimetic systems, enzymes embedded within 3D-printed hydrogel architectures chemically catalyze mineral crys...

Design principle: Design mineralized composite materials by embedding enzymatic catalysts within pre-formed 3D-printed polymeric scaffolds rather than attempting to mineralize bulk materials post-fabrication. This enzy

Active: None (Biomimetic Surgical Clamp (MU9102934-1)), None (Biomimetic Stubble-Cutting Devices (BSCD))

What's actually hard: Translating biological nanoscale chemical homogeneity (zinc enrichment in chitin) into macro-scale steel alloys to prevent material wear and dulling, without inducing brittleness....

Catalyze Chemical Breakdown Peptide molecules · TRL 3/9 · 41 genera

Peptide molecules function as programmable chemical catalysts by arranging amino acids in specific sequences that enable precise molecular recognition and targeted action. These peptides self-assemble into nano-scale structures through weak molecular interactions, creating stable yet flexible frameworks. The peptide chains recognize cancer cell markers and bind to them with high specificity. Once ...

Design principle: Design multi-functional molecular systems by combining modular building blocks with programmable recognition and catalytic properties. Start by identifying the specific molecular markers or structural

Regulate Cellular Processes Eukaryotes

Microtubules are cylindrical protein polymers composed of tubulin subunits which form essential cellular scaffolding and transport networks. Their length is not fixed but instead undergoes continuous remodeling via a process called dynamic instability. Protein caps, particularly those involving tubulin-binding proteins, sit at the ends of microtubules and regulate whether new subunits can be added...

Design principle: This biological system demonstrates a reversible locking mechanism applicable to modular structures. Rather than permanently fixing components, cells use removable molecular caps that toggle between I

Chemically Assemble Mineral Crystals Diatoms (single-celled algae) · TRL 1/9 · 33 genera

Diatoms build their glasslike frustules inside membrane-bound silica deposition vesicles, where proteins, long-chain polyamines, and other organic molecules concentrate dissolved silicic acid and guide it into patterned mineral walls. The cell positions pores, ribs, and layered panels while the silica is still forming, so the finished shell combines low mass with high stiffness and distributes loa...

Design principle: Diatoms synthesize silica-based cell walls (frustules) by using proteins to template and organize mineral precipitation at multiple hierarchical levels. To replicate this approach, engineers should de

State of Commercialisation

Commercial implementations for strategies on this challenge page, drawn from the Atlas Evidence Files.

Function	Product	Company	Year	Status / Notes
Chemically Assemble Mineral Cr	Biomimetic Surgical Clamp (MU910293)	—	—	Active Clamp designed for tissue approximation using bio-absorbable penetrating tips.
Chemically Assemble Mineral Cr	Biomimetic Stubble-Cutting Devices	—	—	Active Precision agricultural cutting blades mimicking ant mandibles for conservation agriculture.

Combination Intelligence

Strategies that address different aspects of the same problem and are not redundant when combined.

Chemically Assemble Mineral Crystals + Chemically Assemble Mineral Crystals

Shared principles: biomineralization, enzymatic catalysis, hierarchical structure, self organization

These strategies share 4 underlying principles including biomineralization and enzymatic catalysis and hierarchical structure. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

Chemically Assemble Mineral Crystals + Chemically Assemble Mineral Crystals

Shared principles: biomineralization, enzymatic catalysis, self organization

These strategies share 3 underlying principles including biomineralization and enzymatic catalysis and self organization. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

Chemically Assemble Mineral Crystals + Regulate Cellular Processes

Shared principles: biomineralization, enzymatic catalysis, self organization

These strategies share 3 underlying principles including biomineralization and enzymatic catalysis and self organization. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

<https://atlasofnature.org/challenge/biomineralisation-room-temperature>

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