PROTECTION

Self-Cleaning Surface Architecture: Superhydrophobic and Superoleophobic Design

How biology achieves contamination resistance without chemical maintenance

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

PROBLEM FRAMING

Surface contamination — particulates, oil, biological fouling — degrades optical, mechanical, and structural performance. Self-cleaning surfaces reduce maintenance burden while preventing performance degradation. Biological self-cleaning relies on geometry, not surfactants.

Application domains: architecture, aerospace, materials

Principle cluster: superhydrophobicity, surface microstructure, hydrophobicity

Physics & Mechanism

Underlying physics

[DRAFT] The lotus effect depends on two structural scales working together: micropapillae (10–100 µm) and epicuticular wax crystal nanostructure (1–5 nm). Water contact angles >150° and roll-off angles <5° are achieved through the Cassie-Baxter wetting state: the surface roughness traps air under the droplet, minimising solid-liquid contact area. In the Cassie-Baxter equation: $\cos\theta^* = r_f \cdot f \cdot \cos\theta_Y + f - 1$, where f is the fraction of solid-liquid interface and rf is the roughness ratio of the wetted area. Self-cleaning occurs because the droplet rolls rather than slides, picking up particulates with diameter > droplet-particle friction threshold (~100 µm). Superoleophobicity (contact angle >150° for oils) requires re-entrant surface features — overhanging geometry that prevents low-surface-energy liquids from penetrating under the Cassie-Baxter state. Springtail cuticles (collembolans) achieve this through mushroom-shaped surface features. Durability remains the primary engineering challenge: Cassie-Baxter states are metastable and collapse under pressure, impact, or abrasion. [END DRAFT]

Biological Strategies

Protect From Excess Liquids Lotus leaf · TRL 3/9 · 136 genera

Carbon nanostructures create superhydrophobic surfaces by mimicking the hierarchical roughness found in nature — similar to how lotus leaves repel water. These structures include carbon nanotubes, nanofibers, nanospheres, nanodiamonds, and graphene, which can be combined with metals, ceramics, or polymers to form composite coatings. The nano-scale texture traps air pockets between microscopic peak…

Design principle: Engineer multi-scale roughness into protective coatings by layering nanoscale features — using carbon-based materials as the foundation — to trap air and create low-adhesion surfaces for liquids. This

Protect From Microbes Sacred lotus · TRL 3/9 · 47 genera

The sacred lotus (Nelumbo nucifera) protects itself from microbial colonization through its leaf surface architecture. The lotus leaf features a hierarchical microstructure composed of microscale papillae topped with nanoscale wax crystals, creating a textured topography that prevents bacterial and algal cells from making stable contact with the surface. When microorganisms attempt to settle on th…

Design principle: Design antifouling surfaces by replicating hierarchical microstructures with nanoscale features that physically disrupt microbial cell membranes. The critical parameters are nanostructure height, spac

Protect From Excess Liquids Lotus leaf; Desert beetle; Spider web · TRL 5/9 · 136 genera

The lotus leaf manages water through a hierarchical surface architecture composed of papillae and epicuticular wax crystals that create microscale and nanoscale structures. These structures establish regions of extreme water repellency (superhydrophobic zones) interspersed with more wettable pathways. When water contacts the leaf surface, it beads and rolls away from hydrophobic peaks while being …

Design principle: Engineer hierarchical surface textures combining superhydrophobic and hydrophilic regions to achieve simultaneous moisture collection and self-cleaning function. Pattern micro and nanostructures—such

Protect From Excess Liquids Salvinia fern · TRL 3/9 · 136 genera

Salvinia species floats on water by engineering a specialized leaf surface architecture that traps and retains a stable air layer when submerged. The plant's microstructured surface—composed of hair-like papillae arranged in specific patterns—creates air pockets that resist water penetration. When the leaf is pushed underwater, water molecules cannot breach the hydrophobic surface, leaving behind …

Design principle: Design submerged or wet-exposed surfaces with hierarchical microstructures that trap and stabilize air layers. The principle: create hydrophobic features at multiple length scales—larger pillars or pa

Protect From Excess Liquids Lotus leaf, Shark skin, Pitcher plant, Insect cuticle · 136 genera

Multiple biological organisms exhibit extreme wetting behaviors through specialized hierarchical surface structures. The lotus leaf develops microscopic papillae combined with waxy epicuticular cells that create superhydrophobic surfaces, causing water droplets to bead and roll away while self-cleaning. Shark skin possesses nanoscale riblet textures in its dermal tissue that reduce drag and repel …

Design principle: Develop hierarchical surface textures by combining multiple length scales of roughness, mimicking biological templates that integrate micro and nanostructures. Select materials or apply coatings with

Combination Intelligence

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

Protect From Excess Liquids + Protect From Microbes

Shared principles: hydrophobicity, superhydrophobicity, surface microstructure

These strategies share 3 underlying principles including hydrophobicity and superhydrophobicity and surface microstructure. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

Protect From Excess Liquids + Protect From Excess Liquids

Shared principles: hydrophobicity, superhydrophobicity, surface microstructure

These strategies share 3 underlying principles including hydrophobicity and superhydrophobicity and surface microstructure. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

Protect From Excess Liquids + Protect From Excess Liquids

Shared principles: hydrophobicity, superhydrophobicity, surface microstructure

These strategies share 3 underlying principles including hydrophobicity and superhydrophobicity and surface microstructure. 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/self-cleaning-surfaces`

Atlas of Nature · atlasofnature.com · Generated 2026-03-21