CAPTURE & FILTER

Osmosis-Driven Energy and Filtration Without Membranes

How biology uses osmotic gradients for transport and power without synthetic membranes

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

PROBLEM FRAMING

Reverse osmosis desalination uses 3–10 kWh/m³. Forward osmosis and pressure-retarded osmosis can recover energy from salinity gradients. Biological systems have exploited osmotic gradients for 500+ million years — for locomotion, turgor-driven growth, and nephron filtration — with greater precision than engineered systems.

Application domains: energy, water_management, materials

Principle cluster: osmosis, microfluidics, capillary action

Physics & Mechanism

Underlying physics

[DRAFT] Osmotic pressure π = iMRT (van't Hoff equation; i = ionicity, M = molarity, R = 8.314, T = temperature). For seawater (35 g/L NaCl, M ≈ 0.6 mol/L): π ≈ 27 atm. This pressure differential is the thermodynamic driving force for ion-selective transport processes. Aquaporins (AQP1) conduct water at 3×10■ molecules/second per channel — 10× faster than passive diffusion through lipid bilayers. Selectivity is ~10■:1 for water over protons, achieved through a hourglass pore geometry (0.28 nm diameter at constriction) and electrostatic exclusion (two asparagine-proline-alanine motifs create a proton barrier). Engineering transfer: 2D material membranes (graphene oxide, MoS_2 nanopores) approach aquaporin selectivity with 100–1,000× higher permeance than state-of-the-art polymeric RO membranes. Kidney nephron counter-current multiplication: a passive mechanism that generates 4× concentration from a 2× gradient through geometric counter-current exchange — analogous to a heat exchanger, but for chemical species. [END DRAFT]

Biological Strategies

Capture, Absorb, or Filter Liquids Welwitschia

Welwitschia mirabilis inhabits one of Earth's driest regions and has evolved leaf morphology and surface characteristics which function as a moisture-harvesting system. This plant's two long leaves develop grooved or channeled surfaces that capture water droplets from fog, dew, and occasional mist. Such structural features create pathways along the leaf surface that guide accumulated moisture towa…

Design principle: Engineers designing water-harvesting systems in arid regions can apply Welwitschia's leaf-channeling strategy by incorporating grooved or ribbed surfaces that guide condensation and moisture toward co

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Capture, Absorb, or Filter Liquids Cotula fallax (buttonweed plant) · TRL 3/9 · 36 genera

Cotula fallax, a fog-harvesting plant, utilizes fine hair fibers covering its leaves and stems to passively collect water droplets from fog. These trichomes are extremely thin biological filaments that protrude from the leaf epidermis, creating a hierarchical surface structure. When fog passes through the plant canopy, water droplets contact these hair fibers and coalesce due to capillary forces a…

Design principle: Engineer fog collection structures using arrays of extremely fine synthetic fibers (hair-like elements) arranged in harp or grid configurations with optimized spacing and orientation. Prioritize fiber

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Capture, Absorb, or Filter Liquids Hummingbirds

This hummingbird tongue operates through a passive mechanical trap mechanism fundamentally different from capillary tube dynamics. As the forked tongue tip enters nectar, the structure expands and opens, allowing fluid to be drawn into grooves along the tongue surface. Upon withdrawal from the flower, the tongue tip contracts and closes, trapping the captured liquid within the channel structure. T…

Design principle: The hummingbird tongue demonstrates a passive fluid-capture system that could inspire engineered solutions for handling low-viscosity liquids without active pumping mechanisms. The key design principl

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Distribute Solids Wood ferns

Wood ferns generate spores within sporangia, specialized capsules containing a ring of cells that control spore dispersal. As water within these cup-shaped cells gradually evaporates, the remaining liquid occupies an increasingly curved meniscus. That curvature generates mounting surface tension forces that pull inward on the cell walls. This cells can sustain this tension only to a critical thres…

Design principle: This system demonstrates how phase change and surface tension can be engineered as a passive energy storage and release mechanism. Water acts as both the working fluid and energy source, with evaporat

Protect From Excess Liquids Lotus leaf · 136 genera

The lotus leaf demonstrates sophisticated fluid control through the integration of hierarchical surface architecture and lipophilic chemistry. Its leaf epidermis features microscopic papillae—cone-shaped cellular protrusions—arranged in a regular pattern across the surface. These papillae are further coated with a waxy epicuticular layer composed of lipophilic compounds that repel water molecules.…

Design principle: Engineer surfaces through biomimetic combination of microscale topography and chemical selectivity inspired by lotus leaf architecture. Create hierarchical textured features—such as conical or columna

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/osmosis-filtration

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