Tailwind FUTURES

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Resilience Game Changers

Acknowledgements

This report is a publication of Tailwind Futures, an investment firm and ecosystem builder focused on accelerating the development and deployment of adaptation and resilience solutions.

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Introduction

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Resilience Game Changers

As climate impacts become more visible and more devastating, **a growing number of academics and researchers are turning their attention to technological innovation and research that could support, enhance and accelerate climate adaptation**. But these efforts are nascent, fragmented, and often lack visibility with the intended end-users or recipients of the research.

This report aims to highlight emerging opportunities by identifying university-originated research that is enabling new climate resilience solutions across industries. These extensive case studies will help inform investors and other funders looking for the next frontier, entrepreneurs who may be exploring their next opportunity, and technology adopters looking for innovative solutions. Understanding the emerging technologies, their maturity and their potential applications may enable these stakeholders to strategically monitor relevant developments and plan targeted engagement.

Many other technological advances are relevant to climate adaptation and resilience but were not included in this report for conciseness. These include nanomaterials (including carbon nanotubes), phase-change materials, advanced formulations of phosphate wildfire retardants and wearable microfluidic biosensors, among others. For the case studies in this report we selected platform technological developments with applications across multiple sectors. The universe of other scientific advances that could support adaptation is vast and we invite readers to explore other technologies and relevant resilience applications.

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Adaptation & Resilience (A&R) Solutions

Adaptation and resilience (A&R) solutions are those that prepare, prevent, respond to and/or enable recovery from climate shocks and stressors.

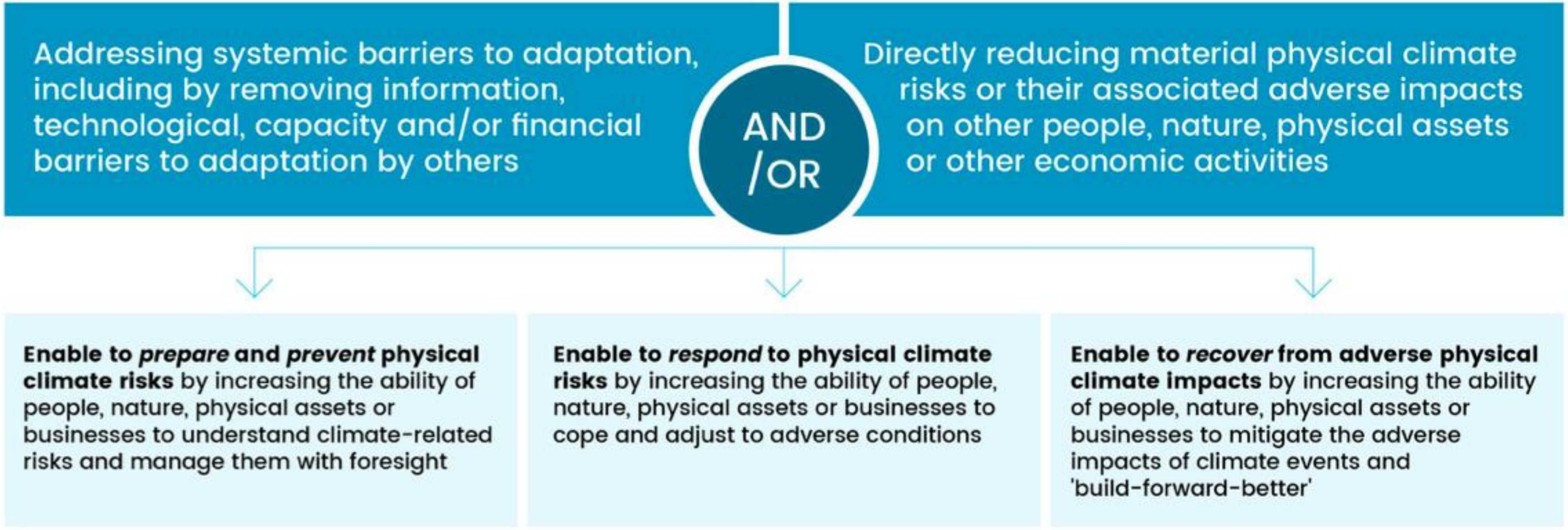


Figure source: GARI, 2024 as published in The Adaptation & Resilience Innovation Playbook: https://www.tailwindfutures.com/wp-content/uploads/2024/12/Final-Tailwind-Playbook-12.12.24-2.pdf

Tailwind Futures' A&R Taxonomy

Tailwind Futures' Adaptation & Resilience Taxonomy breaks down eight themes and 36 sectors of the economy where adaptation solutions are needed. Technology transfer offices and researchers may consider this framing to add an A&R lens to their research and identify commercialization opportunities.

From Lab to Market: Challenges & Opportunities

University Research Unlocks Innovation

University-originated research has paved the way for advanced technologies and improvements across every industry.

Many products and infrastructure we rely on today use materials that originated as academic, fundamental research. **Even when they aren't explicitly focused on climate change, research across university departments has the potential to be applied to critical challenges presented by climate change.**

Resilience technology is an emerging topic that is often not explicitly tied to funding opportunities. Or, when climate adaptation-specific funding or programs do exist, researchers may not be aware of them. Because the physical impacts of climate change are felt across many industries and sectors, **even research that may not traditionally be viewed as climate-related holds potential to contribute to climate adaptation challenges**

Image Source: SAHARAT – stock.adobe.com

University Research Holds Untapped Potential

In many cases university research findings are not actively applied beyond the lab and research journals. Based on data from an AUTM survey of universities in 2025,[1] US university research led to 28,278 invention disclosures and 13,729 patent applications across all industries, but only 1,095 startups dependent on university IP formed that year. This indicates a discrepancy between the amount of new technology universities patent and the amount of technology released into early-stage market.

Anecdotal evidence based on conversations with technology transfer offices from several large universities provides further validation of this issue, highlighting the wealth of innovation held by university tech transfer offices. **This is an opportunity to harness this untapped innovation to address social and economic challenges, including those presented by climate change.**

U.S. Academic Technology Transfers, 2025

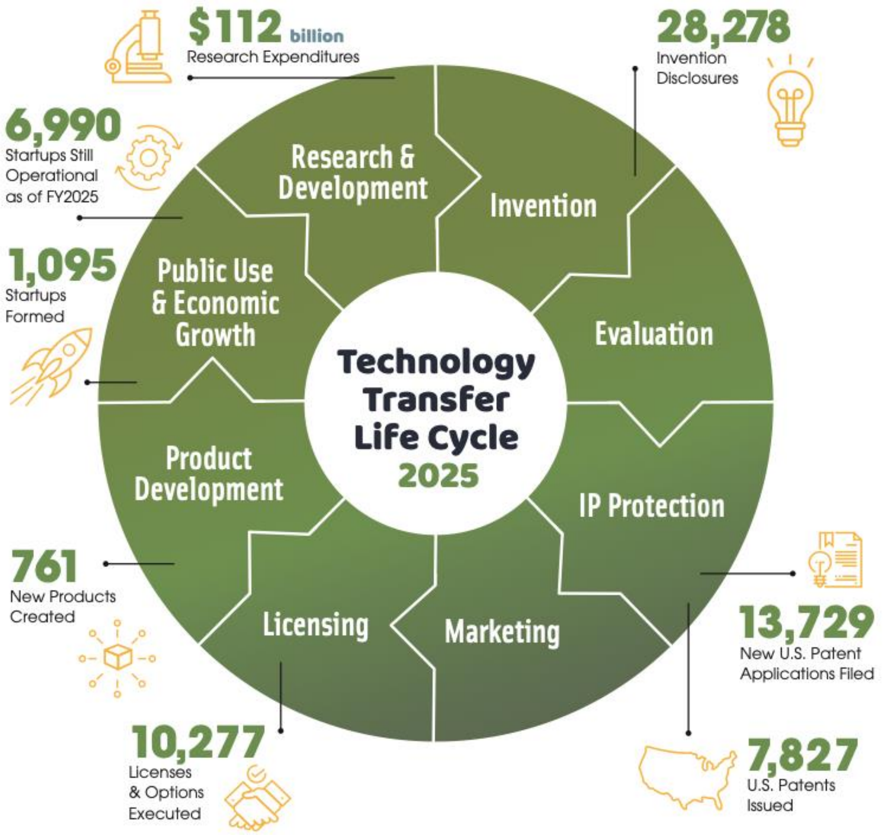
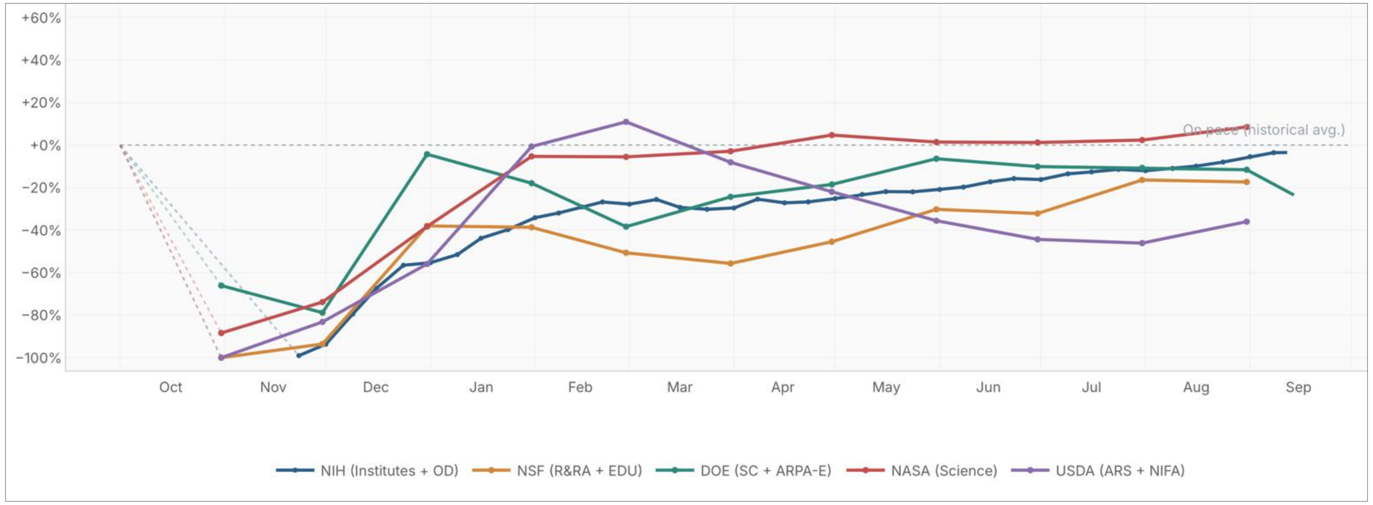


Figure Source: AUTM (2026): https://autm.net/surveys-and-tools/tech-transfer-infographic

University Research Funding Headwinds

FY2026 Award-Making Pace vs. Historical Average



Source: Tracking Science Spending

University research faces headwinds from the changes in federal funding. While the federal government has traditionally been the largest funder of university research, at the start of May the National Science Foundation had awarded only 55%[2] of the share of grants it typically awards by that time, and NASA is the only science agency to have awarded 100% of its typical share of grants as of the start of September.

This reduction in funds has led to cuts in university research programs. While federal grants remain essential for university research, the stage between basic research and early product development has always been challenging to fund and is particularly critical now. Commercial, corporate and philanthropic capital is not deployed broadly for early-stage research and development, but there are models that have worked well and can be replicated. Programs including Greentown Labs,[3] MIT Engine,[4] Berkeley Bakar Labs[5] and Elemental Impact[6] specialize in connecting very early tech ventures with the partners and resources they need to de-risk, obtain follow-on funding and scale commercially. They also each have large investment funds affiliated with their incubators. The breadth and depth of research underway in the US and globally offers ample opportunity for new partnerships that harness innovations and bring much needed solutions to market.

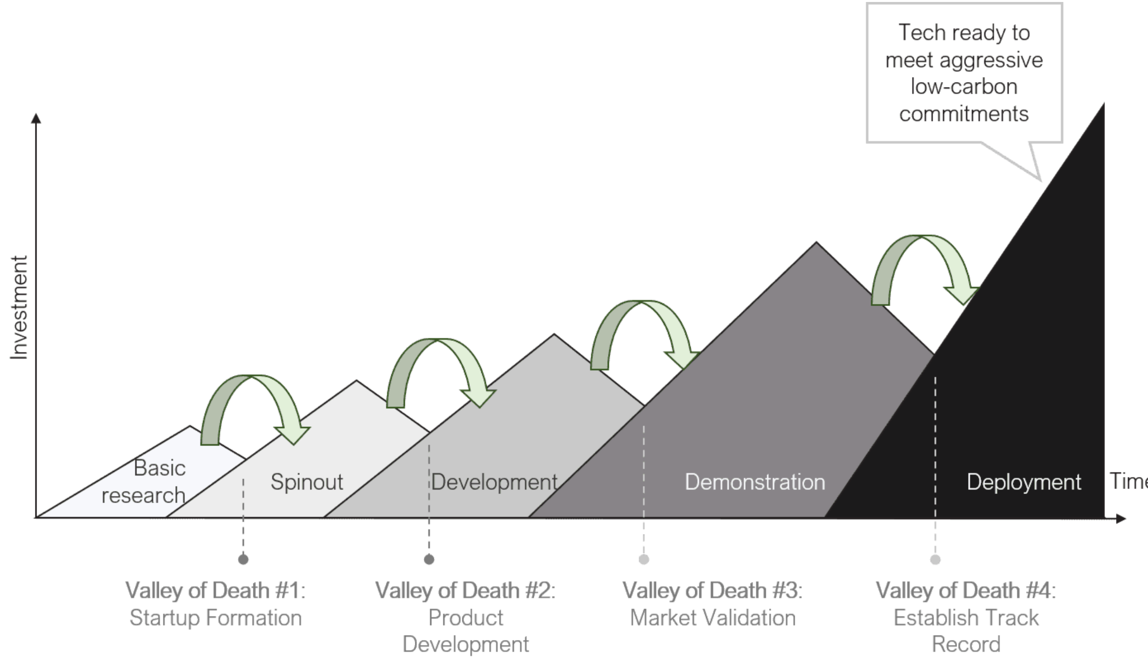
Resilience Tech Faces Known Challenges

Valleys of Death

A&R technologies face the same "valleys of death" as other hard tech startups: bringing a new product to market relies on constant iteration, testing, customer discovery and creating a new market. Companies that receive help and support to bridge these valleys fare better than their competitors.

Many important A&R innovations rely on hard tech, deep tech or "Tough Tech" which have higher capital costs, specialized equipment requirements and longer R&D timelines, compared to software. In addition, many customers of climate technology tend to be conservative, risk-averse incumbents rather than enthusiastic early adopters in information technology or companies whose core business model depend on innovation and IP creation like pharmaceutical companies.

Valleys of Death for Climate Tech Commercialization



Source: Third Derivative

Replicating Known Solutions

Accelerators and incubators help startups cross the Valleys of Death

There are over 60 accelerators and incubators focused on climate tech in the US. While many have focused on mitigation solutions to date, several have begun integrating resilience programming, and there is an opportunity to harness lessons-learned in mitigation to scale resilience solutions.

Accelerators are term-defined programs (ex. 3-6 months) focused on helping startups meet certain milestones (product market fit, fundraising, commercial revenues, etc.).

Fellowships have emerged as a separate category, with Activate and Breakthrough Energy Fellows as the largest climate focused programs. These programs provide funding to innovators pre-incorporation and through Seed stage, for typically up to 2 years. These programs share common features with incubators and accelerators, such as training and mentorship, but often place more emphasis on the growth of the individual rather than the growth of a whole company.

Incubators tend to operate on a longer term (18-36 months on average), are more flexible with programming but typically offer mentoring, investor programs, pitch/demo days, and access to community. They often - but not always - offer physical space and equipment. Some incubators also host accelerator programs within them both for member companies and for outside companies joining these programs.

Examples of Deeptech Incubators

Greentown Labs, an incubator based in Boston and Houston, helps scale climate and energy startups. It hosts a community of startups in flexible lab and office space, designed for testing innovative deep-tech and brings together an ecosystem of corporates, investors, inventors and entrepreneurs.

The Engine, an incubator and accelerator based at MIT, focuses on scaling early-stage "Tough Tech" companies from research breakthroughs to commercial traction. It defines Tough Tech as "transformational technology that solves the world's most important challenges through the convergence of breakthrough science, engineering and entrepreneurship."

Bakar Labs, based at UC Berkeley, Initially focused on biotech, and recently launched an Energy & Materials pilot incubator providing lab space, mentorship and investor connections. The Lab emphasizes its position in the heart of a leading research university.

Building the Ecosystem

While the incentives and near-term goals vary, there is a broad set of researchers, investors, corporations and governments who all want A&R solutions to scale more rapidly. Identifying each group's priorities is the first step towards collaboration.

	Goal	What Is Required Before the Goal Can Be Reached	Opportunities to Collaborate with Other Stakeholders
Researcher	Journal publications	A hypothesis to test and research funding	When designing research, engage with potential end-users around their needs
Grant Giver (Public or Philanthropy)	Mission-aligned impact	Clear hypothesis with explicit connection to real-world impact	Engage with potential downstream users of tech, to help early R&D align with longer-term user needs
Technology Transfer Office	Patents, licenses & commercial agreements	New technology or discoveries and market interest	Raise awareness among researchers of commercialization options; translate and promote university tech to entrepreneurs, investors and industry
Entrepreneur	Profitable company	A technology with a clear use case for a certain market or markets	Engage with universities to explore the next frontier of emerging tech
VC Investors	Invest in a startup with a goal to return 10 to 100x the initial investment	For early-stage investors: a working product (or prototype), Product market fit, a strong team, and clear rights to the technology	Share insight on what's required for VC funding with researchers early in the process
Corporate / Industry	Product/service that increases revenue or reduces costs	A solution that is reliable, available, certified (or certifiable) under relevant standards, protected from supply problems, and fits into existing operations and procurement workflows	Sponsor university research to help shape projects examining real needs; participate in pilots to inform product development

This table is informed by and builds upon Table 1 in the Duke University post Turning University Innovation into Investable Climate Adaptation and Resilience Solutions

Identifying Resilience Game Changers

Identifying Resilience Game Changers

This report explores several potentially game-changing technologies with broad applications across many of the climate impacts identified below based on our review of academic research in the United States and United Kingdom that could be related to climate adaptation and resilience.

We examine technologies that are in different stages of development, exploring the role universities have played, the challenges and successes of commercialization to date and what may be coming on the horizon.

Examples of climate-related Impacts

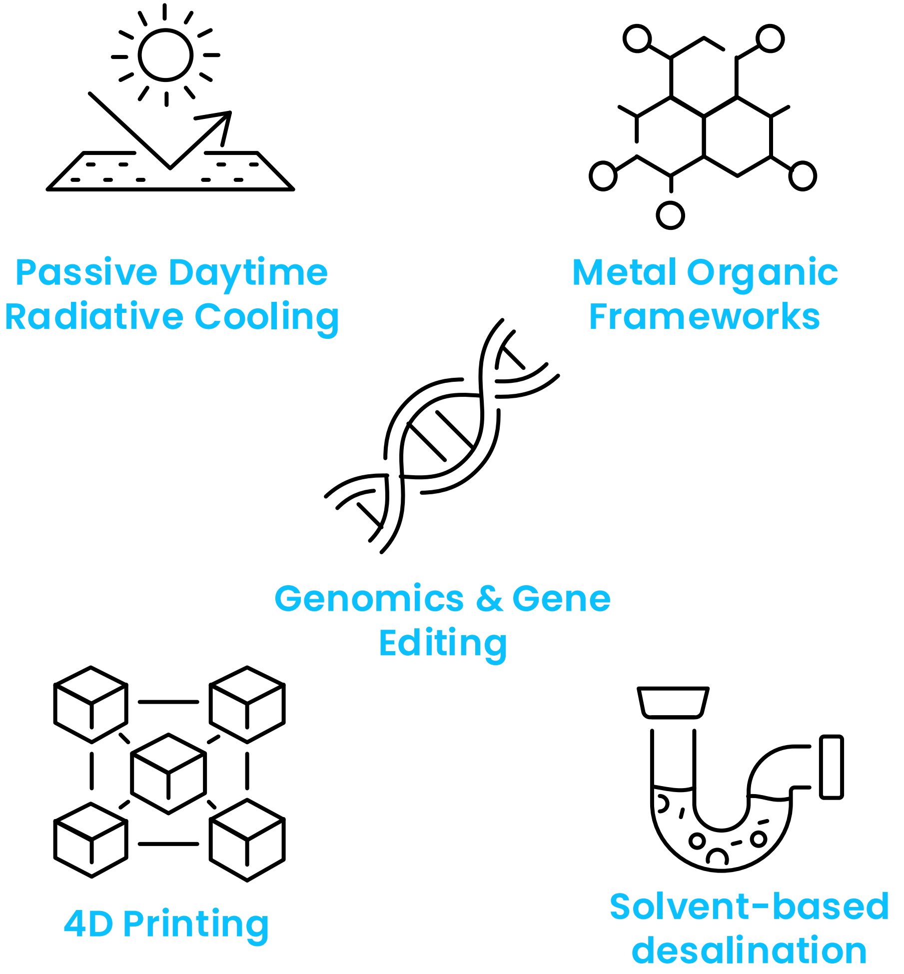
Ecosystems	Food, Agriculture & Foresty	Cities & Communities	Water & Sanitation	Health	Infrastructure	Industry & Commerce
• Increase in forest pests • Coral bleaching	• Reduced quality of ag land • Increased for crops and livestock • Algal blooms • Impacts on food storage and distribution • Threats to worker health, safety & productivity	• Damage to private and public buildings • Danger to occupants or to building content	• Reduced water availability • Damage to critical water infrastructure • Water contamination due to extreme events, table salination, etc.	• Increased malnutrition • Increased mortality and injury from extreme events • Increase in food-borne, water-borne and vector-borne disease • Increase in cardiovascular and respiratory disease	• Disruption to key energy, communication or transportation infrastructure during extreme events • Chronic disruptions from tidal flooding, erosion, subsidence, extreme heat, etc.	• Increased energy demand and prices • Working hours lost

Game-Changing Resilience Technology

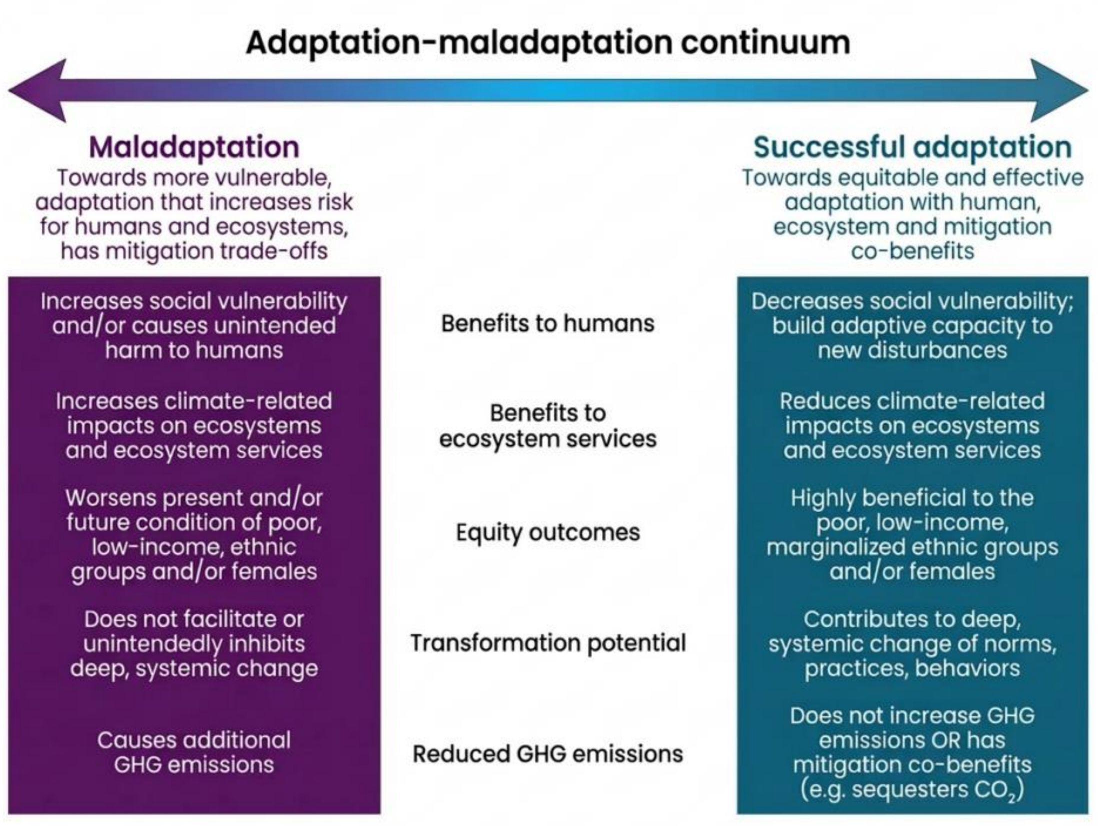
This report provides deep dives on five technologies with resilience applications across industries

The first three technologies, **passive daytime radiative cooling**, **metal organic frameworks** and **genomics & gene editing**, were unlocked by breakthroughs over a decade ago and have been powering spinouts for years. However, continuing R&D is discovering new resilience applications of these technologies across a range of sectors, while technological advances continue to drive down costs and increase potential commercial opportunities.

The next set of technologies we feature include **4D printing** and **solvent-based desalination**, which have received more R&D attention recently, with ongoing discoveries shining light on potential resilience applications in healthcare and industry respectively. There is still much to discover in terms of both technological and financial feasibility at scale, but these could underpin potentially game changing innovations over the next decade.



Maladaptation Considerations



Source: Tailwind Futures, adapted from Figure 17.10, IPCC AR6 WG2

For each technology, we include a brief assessment of potential maladaptation risks, based on Tailwind Futures' [Maladaptation Diligence Toolkit.](#)[8]

According to the Intergovernmental Panel on Climate Change, maladaptation[9] refers to "actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence."

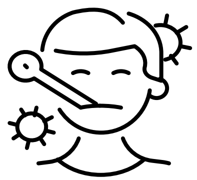
Maladaptation risks, when identified early, are frequently manageable and addressing them can ultimately improve the solution and investment outcomes. By considering them early in the commercialization process, these risks can be considered alongside others in a holistic risk mitigation plan.

Passive Daytime Radiative Cooling

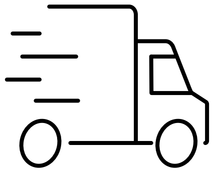
At a Glance

Passive daytime radiative cooling (PDRC) is an innovation that enables materials that passively cool themselves to beneath ambient temperature, even in direct sunlight.

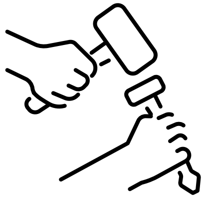
Ways PDRC can build climate resilience:



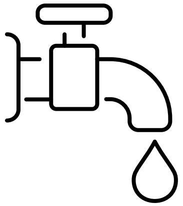
Reduce heat-related mortality and morbidity



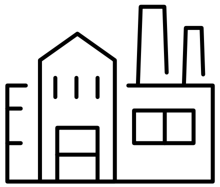
Reduce risks to food storage & distribution



Improve worker health and safety



Improve water security



Improve industrial cooling

Example Startups:

- AssetCool produces PDRC coating for transmission lines to improve conductivity during extreme temperatures.
- Chill Skyn sells a PDRC coating that can be applied to a variety of surfaces for a cooling effect.
- Dewpoint is a University of Sydney startup creating PDRC paint that cools and harvests water.
- Heat Inverse produces a PDRC film that can be applied to buildings, trucks and other equipment to reduce cooling demands.
- Pirta sells a PDRC paint that can be applied to a variety of surfaces for a cooling effect.
- SkyCool Systems produces panels that passively cool vapor compression air conditioning and refrigeration systems, improving their energy efficiency.

PDRC: The Technology

Rooftop radiative cooler

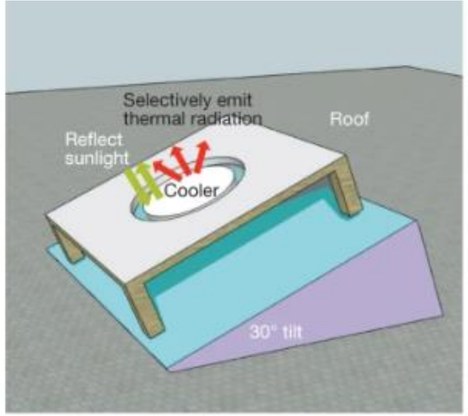


Image Source: SkyCool Systems

Passive daytime radiative cooling (PDRC) enables structures in direct sunlight to cool beneath the ambient air temperature, without requiring external energy input.

All physical matter radiates heat to its environment, but usually only until its internal temperature reaches equilibrium with its near surroundings. Passive cooling below ambient temperatures has long been observed through nighttime radiative cooling, where a substance exposed to a clear night sky sheds heat toward the cold of outer space even after dropping below the temperature of the immediate air. This relies on the portion of the electromagnetic spectrum known as the "atmospheric window,"[10] a gap in the spectrum where the atmosphere lets heat escape rather than trapping it. Historically, early civilizations utilized the natural infrared emissivity of water placed in shallow, insulated basins to achieve this effect, essentially "harvesting" the cold of the universe to create ice in the desert.

While these early methods were limited to the night, a 2014 materials science breakthrough[11] made daytime radiative cooling possible for the first time. Previously, the heat gain from direct sunlight overwhelmed any thermal radiation escaping to space. **By engineering surfaces that integrate high solar reflectance with intense emissivity within the "atmospheric window," scientists demonstrated that synthetic materials can now maintain sub-ambient temperatures even under the peak intensity of the sun.**

PDRC: The Technology

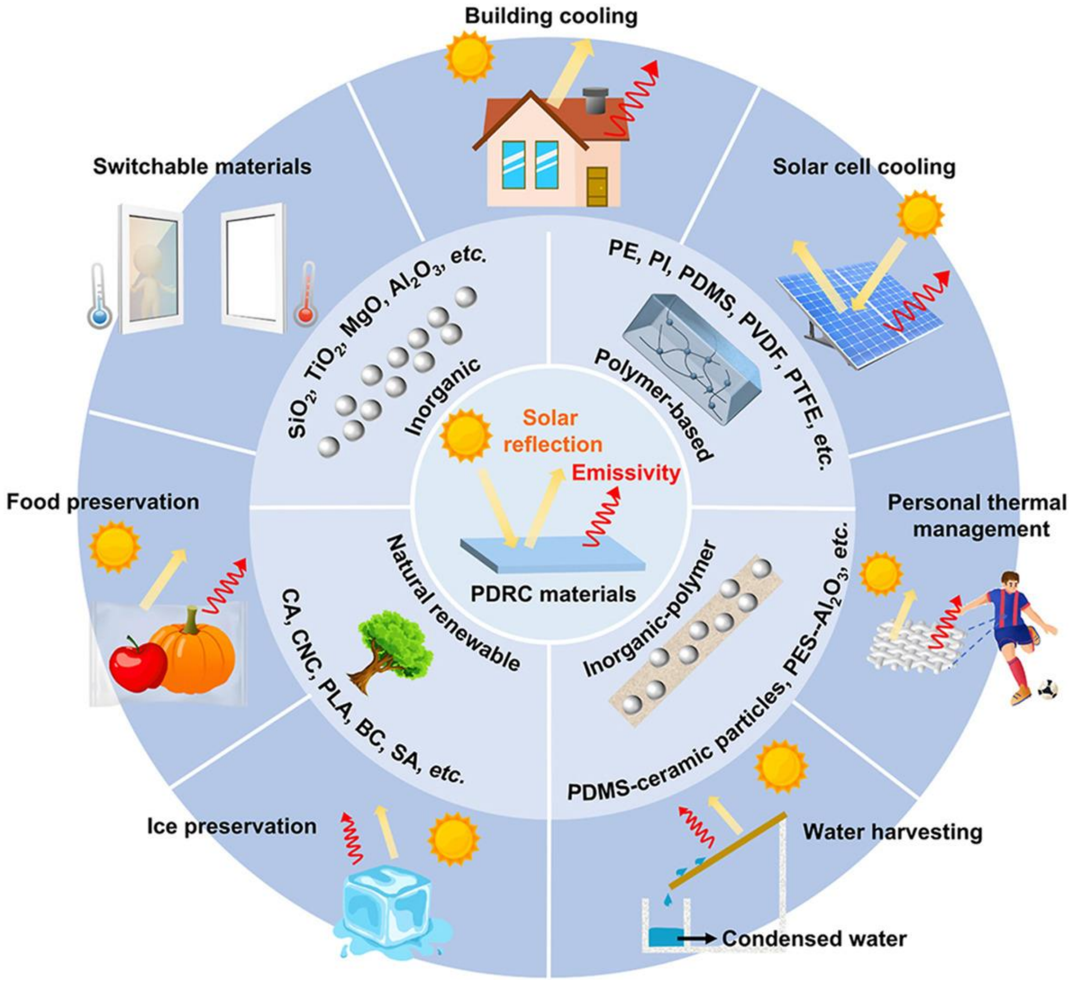


Image Source: Feng et al (2024)

The initial Stanford-developed photonic radiative cooler consisted of seven alternating layers of hafnium dioxide and silicon dioxide of varying thicknesses, on top of 200 nm of silver, which are all deposited on top of a 200-mm silicon wafer.

Since this initial breakthrough, research on PDRC has unlocked a range of applications of the technology, across multiple sectors and climate impacts.

For example, SkyCool Systems, spun-out of the Stanford Ginzton lab, commercializes this PDRC technology to improve the efficiency of air conditioning systems, by radiatively cooling the water vapor compression system using large, roof mounted panels that reject heat.

PDRC: Resilience Applications

Replacing or Reducing Energy-Intensive AC to Cool Buildings

PDRC can cool buildings without requiring energy in certain environmental conditions. PDRC reduces greenhouse gas emissions but also eases the burden on electrical grids by lessening energy demand for cooling during peak hours, reducing facilities' exposure to electricity price spikes and power outages, both of which are likely to become more common as extreme heat and storms stress power grids.

In areas where air conditioning is not widespread but increasing temperatures are threatening occupant health and comfort, PDRC technologies could offer some cooling solutions to reduce the amount of required air conditioning uptake and associated emissions. However, it's unlikely that this technology alone could stand in for air conditioning, especially in humid places, given its reduced effectiveness under certain conditions, such as high humidity or cloud cover.

Using PDRC to cool buildings instead of, or in combination with, traditional air conditioning also reduces the urban heat island effect. Not only do traditional air conditioning units expend energy to reduce the temperature inside an enclosed space, they also expel slightly more heat than they extract. In aggregate, this contributes to further warming a city as each individual air conditioner slightly heats the air outside. PDRC avoids this problem by radiating heat not to the atmosphere but through the atmosphere, and out to space.

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PDRC: Resilience Applications

Reducing Energy Demand and Costs for Industrial Assets

SpaceCool film on a beverage processing plant

Image Source:: SpaceCool

PDRC cooling technology can also reduce energy demand and associated costs for manufacturing, commercial or industrial assets. For example, SkyCool's roof panels use PDRC film to cool fluids[12] that flow in from a connected air conditioning or refrigeration system. At a supermarket in California, the panels were used to pre-cool the refrigeration system, leading to 15% energy savings and reduced peak power demand.

This could also help reduce energy demand at other assets that rely on consistent cooling, such as factories, storage facilities or data centers. For example, a packaging plant with SpaceCool film experienced lower temperatures and reduced solvent evaporation[13] compared to its operations with no film.

PDRC: Resilience Applications

Reducing Food Spoilage

PDRC film installed on refrigerated trucks

Image Source: HeatInverse

Cooling without electricity is beneficial for food crop preservation in remote areas, or areas with unreliable electricity, providing a solution for storing and transporting temperature sensitive foods or even vaccines during increasingly frequent extreme heat.

For example, the MIT Device Research Laboratory[14] has experimented with combining evaporative and radiative cooling to extend perishable food's shelf life, even in high heat and humidity.

Maintaining low temperatures in refrigerated trucks will become more costly as temperatures rise, but applying PDRC film could reduce these costs while reducing the risks of food spoilage during extreme heat events. Ithaca based startup, Heat Inverse, piloted its CoolFilm[15] on New Transport Applications (now part of DHL) trucks, demonstrating a 28% reduction in cooling fuel needs, reducing both costs and emissions.

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PDRC: Resilience Applications

Supporting Atmospheric Water Generation

PDRC's ability to chill a material can improve the efficiency of atmospheric water generation (AWG) technologies.

Many AWG devices work by cooling a surface below the atmosphere's dew point, condensing the gaseous water vapor in the atmosphere into liquid water on that surface, to be collected as drinkable freshwater. Passive daytime radiative cooling uses thermal access to ultracold outer space to radiatively cool the surface below the dew point, leading to faster condensation and less energy consumption than in systems[16] relying solely on traditional convective condensers.

For example, University of Sydney startup, Dewpoint's PDRC paint[17] cools buildings while harvesting water, integrating into rooftop water collection systems.

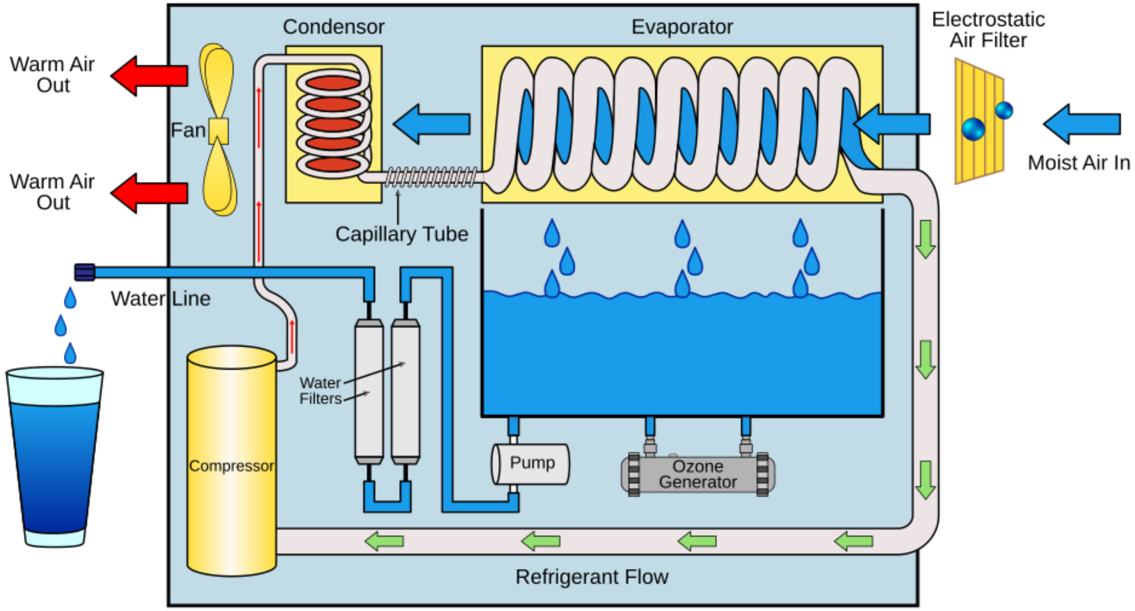

Figure source: Wikimedia Commons, through the Creative Commons Attribution-Share Alike 4.0 International, 3.0 Unported, 2.5 Generic, 2.0 Generic and 1.0 Generic license.

PDRC: Maladaptation Risks

PDRC by default will continue to cool surfaces to beneath ambient temperatures without energy input. This is highly beneficial for extreme heat situations. However, before applying PDRC somewhere that also experiences extreme cold, a cost benefit assessment would help identify the potential trade-offs of the system across year-round climate and weather patterns.

The efficiency of PDRC is affected by environmental conditions that reduce the atmospheric window through which heat is released. **High humidity[18] and high cloud cover[19] among other factors tend to reduce the efficiency of PDRC**, with implications for where this technology may be most viable. It will be important to both understand any location-specific factors that will affect cooling efficiency in target markets to ensure performance is not over-estimated and also to consider design approaches that optimize PDRC performance in places that are in high need of efficient cooling, such as those near the equator.

The materials used in PDRC products can carry their own risks. There are a range of materials[20] that can be made to have PDRC properties, including polymers, wood, and inorganic compounds, including ceramics and metallic composites. When considering a PDRC-based technology for a specific application it will be important to identify the materials used and the associated environmental and human health impacts that may need to be managed.

Example of PDRC form factor

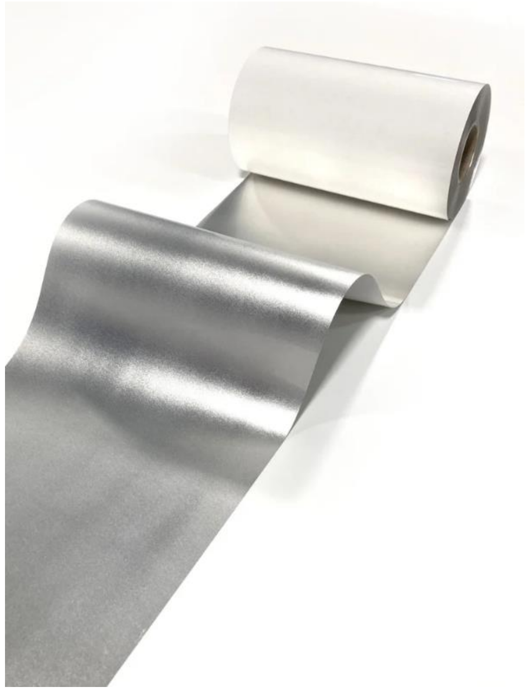

Image Source: HeatInverse

PDRC: The Next Wave of Innovation

PDRC experiment on a roof in Japan

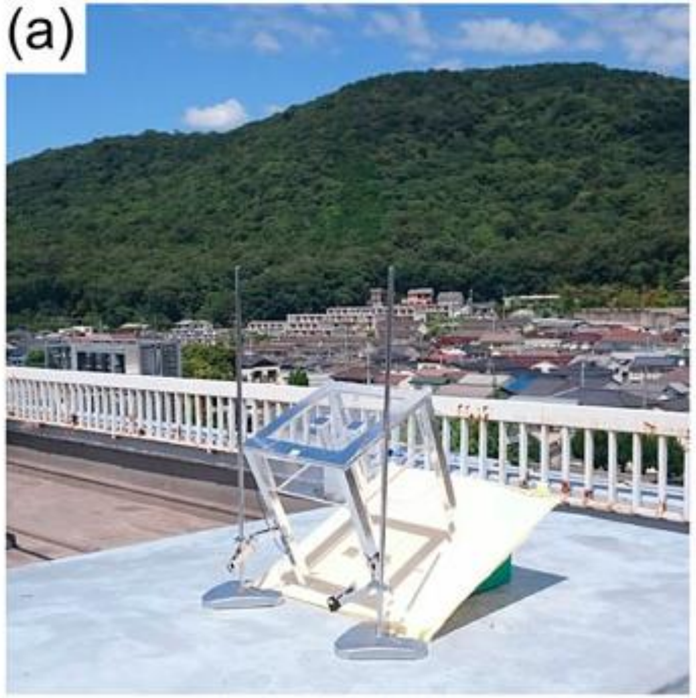

Figure Source: *Suichi et al (2018)*

While PDRC is already being commercialized, **the next frontier of PDRC innovation is principally focused on driving down cost at scale and demonstrating field durability.** An important part of this ongoing testing and research will be to examine the performance of different PDRC materials under different weather conditions that interact with the atmospheric window and effect cooling efficiency, as discussed above. **Researchers are examining different combinations of materials to optimize performance under various weather conditions.**

Momentum is building in support of these objectives. For example, climate tech accelerator Third Derivative launched a PDRC open innovation pilot program[21] in October 2025, to provide promising technologies real world feedback and pathways to scale. **To accelerate the curve of adoption, Third Derivative is facilitating pilot programs, testing PDRC solutions on informal housing in India and commercial buildings in the United States.** The results of these trials will be published as open-source data to spur broad commercialization development of the technology.

PDRC: The Next Wave of Innovation

While pilots demonstrated that the technology can be effective, to scale broadly it will need system level integration with industrial systems, which is still early stage.

PDRC also has potential to improve cooling in outdoor spaces. Traditional metal shade structures absorb solar energy over time and radiate that heat downward onto the people or livestock they're meant to protect. PDRC does the opposite as the material "draws" heat out of the body of people under the shelter. In 2021 Arizona State University partnered[22] with the City of Tempe to pilot PDRC cooling film on bus stops, finding a significant improvement in rider comfort. While the City of Tempe expressed interest in integrating these films into future bus shelter design, it has yet to be adopted consistently.

Early work is being developed on applying PDRC to thermoregulating textiles,[23] hardhats, and other personal protective equipment designed to cool individual wearers. This would unlock further personal safety protection for laborers exposed to extreme heat. For example, the Hsu Group[24] at the University of Chicago has been working to integrate PDRC elements into everyday clothing.

Some scientists speculate that since PDRC sheds heat through the atmospheric window and out of the planetary system all together, at a much larger scale it could theoretically have an impact on reducing global average temperature.[25]

PDRC film on a bus stop in Tempe, AZ

Image Source: Fox10 Phoenix

PDRC fabric could help protect workers

Image Source: Nature

Metal-Organic Frameworks (MOFs)

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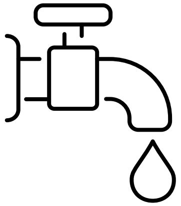
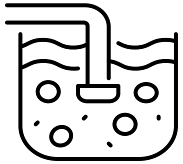
At a Glance

Metal-Organic Frameworks (MOFs) are a class of ultra-porous crystalline materials with extraordinarily large internal surface areas, enabling them to capture, store, and release specific molecules with remarkable efficiency.

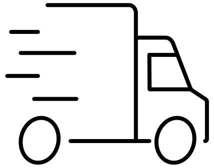
Ways MOFs can build climate resilience:



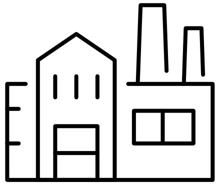
Improve water security



Address water table salination and contamination



Reduce risks to food storage & distribution



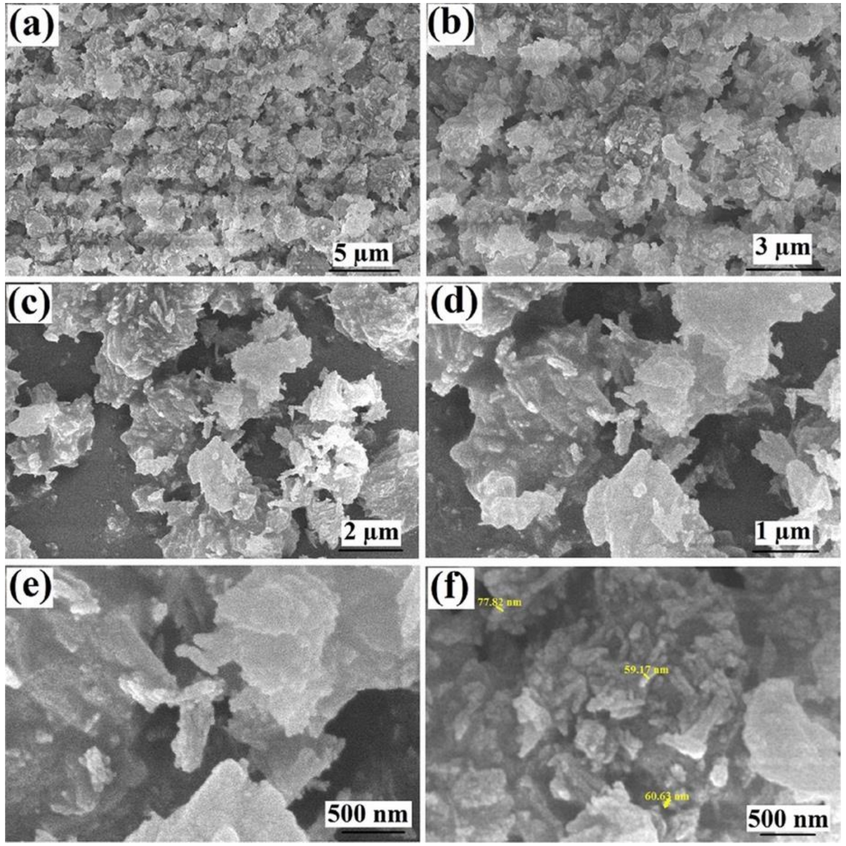
Improve industrial cooling

Example Startups:

- Aquaporo creates MOF-based atmospheric water generation tech for efficacy and energy efficiency at very low humidities, spun out of research conducted at Jordan's Royal Scientific Society.
- Immaterial is a Cambridge university spinout that identifies MOFs for specific use cases and manufactures them in an optimal monolithic form.
- NuMat Technologies is a Northwestern University spinout manufacturing MOFs themselves at commercial scale for gas storage, separation, and water-related applications.
- Transaera is a MIT-based startup using MOFs to reduce humidity and improve the efficiency of cooling systems.
- WaHa uses ultra-high porosity MOFs to capture large amounts of water vapor from even low humidity air, and was spun out of the Yaghi Lab at UC Berkeley in 2018.

MOFs: The Technology

Images of amino-MIL-68(Al) metal-organic framework at different magnifications.



Source: Rahmani A. et al. Facile fabrication of amino-functionalized MIL-68(Al) metal-organic framework for effective adsorption of arsenate (As(V)). Scientific Reports 12, 11865 (2022). Licensed under CC BY 4.0.

Metal-Organic Frameworks (MOFs) are crystalline materials constructed from two building blocks: metal ion clusters, which act as nodes, and organic molecules, which act as connecting struts or "linkers." When assembled, these components form a rigid, repeating lattice structure riddled with nanoscale pores. The result is a material that is mostly empty space: a single gram of certain MOFs can contain an internal surface area exceeding 7,000 square meters,[26] roughly equivalent to a football field. **This extraordinary porosity is what gives MOFs their power.** Because so much surface area is available inside the material, MOFs can adsorb, or capture on their surface, enormous quantities of gas or liquid molecules relative to their size.

MOFs are also highly tunable. By selecting different combinations of metal nodes and organic linkers, researchers can engineer MOFs to selectively target specific molecules, such as water vapor, carbon dioxide, heavy metals, or ethylene gas. These purpose-made MOFs capture their target molecules without an energy input. Energy input is needed, often in the form of heat, to release the captured molecule. The amount of energy required is a critical parameter to optimize for commercial viability.

MOFs: The Technology Cont'd

The concept of connecting metal ions with organic linkers had been explored in chemistry for decades, but early structures were fragile and collapsed when their pores were emptied of solvent molecules, rendering them impractical. The defining breakthrough came in 1999, when chemist Omar Yaghi of UC Berkeley and colleagues published a landmark study in Nature[27] demonstrating MOF-5, the first metal-organic framework with a stable, permanently porous structure. MOF-5 retained its rigid crystalline lattice even after all guest molecules were removed, **proving for the first time that these materials could function as robust, reusable molecular sponges.**

This discovery catalyzed an explosion of research. Over 90,000 MOF structures had been synthesized by 2020,[28] with that number surpassing 100,000 by 2025,[29] and thousands of new structures published each year. Yaghi's group and others continue to push the boundaries of what MOFs can capture and under what conditions, steadily expanding the frontier of their practical utility. In recognition of this body of work, Yaghi shared the 2025 Nobel Prize in Chemistry[30] with Susumu Kitagawa of Kyoto University and Richard Robson of the University of Melbourne for their collective role in developing MOFs.

MOFs' combination of massive surface area, tunability, and energy efficiency positions them as a platform technology for multiple climate adaptation challenges

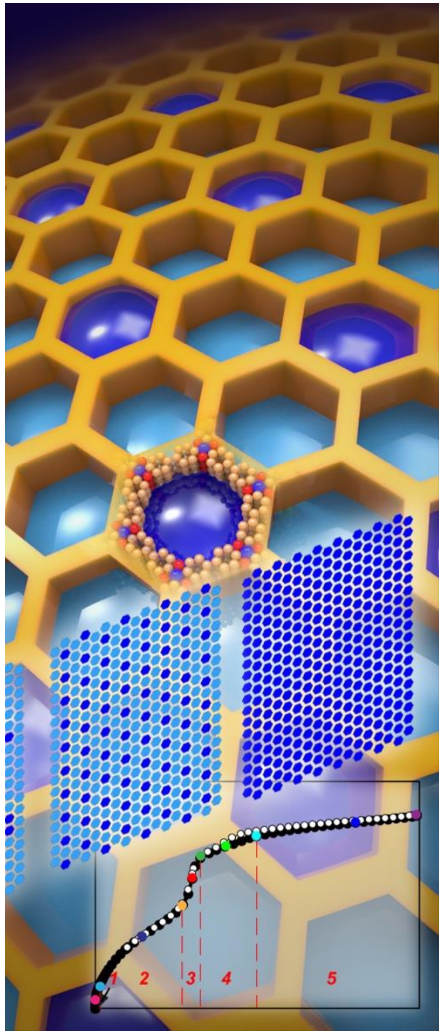


Image Source: Lawrence Berkeley Lab

MOFs: Resilience Applications

Water Purification and Decontamination

Researchers have engineered MOFs to selectively adsorb specific pollutants, including heavy metals such as lead, arsenic, and mercury,[31] as well as organic contaminants and excess fluoride. **Because MOF pore sizes and surface chemistry can be precisely tuned, they can target individual contaminants with a level of selectivity that conventional filtration materials like activated carbon cannot easily match.**

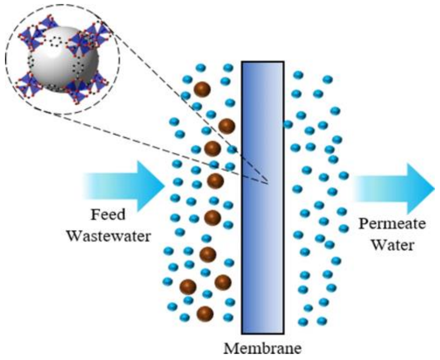


Image Source: Kiteto et al (2024).

Extreme weather events such as hurricanes, floods, and wildfires frequently compromise water treatment and distribution systems[32], creating acute public health risks. In many regions, climate change is also worsening chronic water quality problems: prolonged drought degrades source water quality, rising sea levels drive saltwater intrusion into coastal aquifers,[33] and higher water temperatures promote harmful algal blooms.[34]

MOF-based water treatment could provide targeted, deployable solutions for both acute and chronic contamination scenarios. For example, following major wildfires, damaged distribution systems have leached benzene and other volatile organic compounds into drinking water[35] at concentrations that conventional activated carbon can miss. Laboratory work on MOFs engineered to capture PFAS illustrates the kind of contaminant-specific selectivity that could help fill these gaps. Their high adsorption capacity per unit mass makes them particularly suited to portable or modular filtration systems that could be deployed rapidly after disasters or installed in communities facing chronic water quality degradation. Research in this area is still largely at the laboratory stage, but it is an active area of exploration.

MOFs: Resilience Applications

Improving the Efficiency of Atmospheric Water Generation (AWG)

AWG technologies extract water vapor from ambient air and convert it into liquid water. This can provide freshwater that does not depend on rainfall, serve industrial manufacturing uses that rely on ultra-pure water, and provide decentralized and emergency water sources when municipal water infrastructure is unavailable. However, traditional cooling-condensation AWG systems are energy-intensive and less effective in dry or cool environments.[36] Desiccant-based AWG offers an alternative, using materials that absorb water vapor directly from the air and release it when gently heated. But conventional desiccants still have limited performance in very dry conditions.[37]

In 2017, researchers in Omar Yaghi's laboratory at UC Berkeley pioneered the use of MOFs as desiccant materials for AWG.[38] **MOFs' extraordinarily large internal surface areas allow them to capture water at relative humidity levels as low as seven percent, which is a typical midday desert condition.** The Yaghi lab has since spun out WaHa[39] (founded in 2018) and Atoco[40] (founded in 2020), which are startups commercializing MOF-based AWG. Other ventures such as Aquaporo,[41] which is based on MOF research by Kyle Cordova's research group at Jordan's Royal Scientific Society, are commercializing similar technologies.

Water harvesting prototype

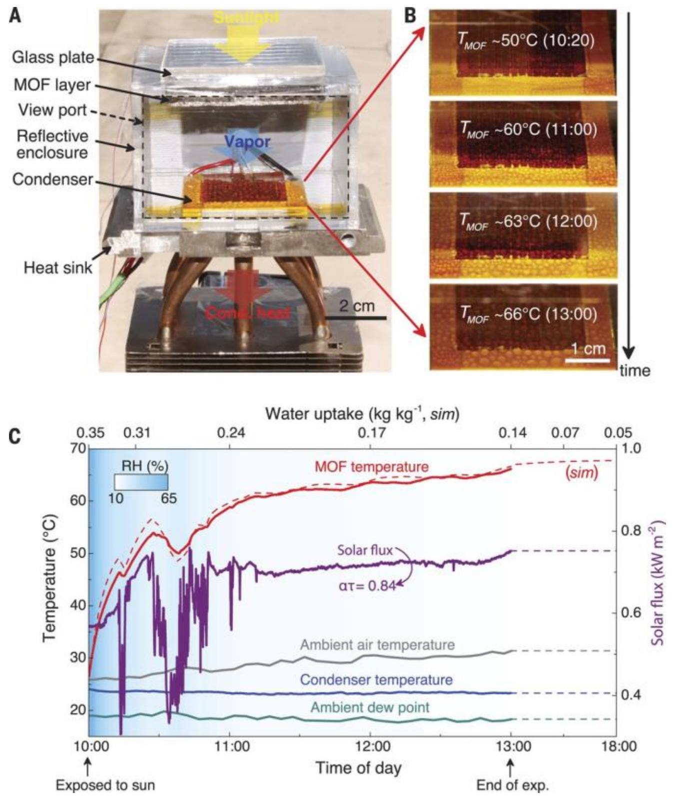


Figure Source: *Kim et al (2017)*

MOFs: Resilience Applications

Increasing Cooling Efficiency

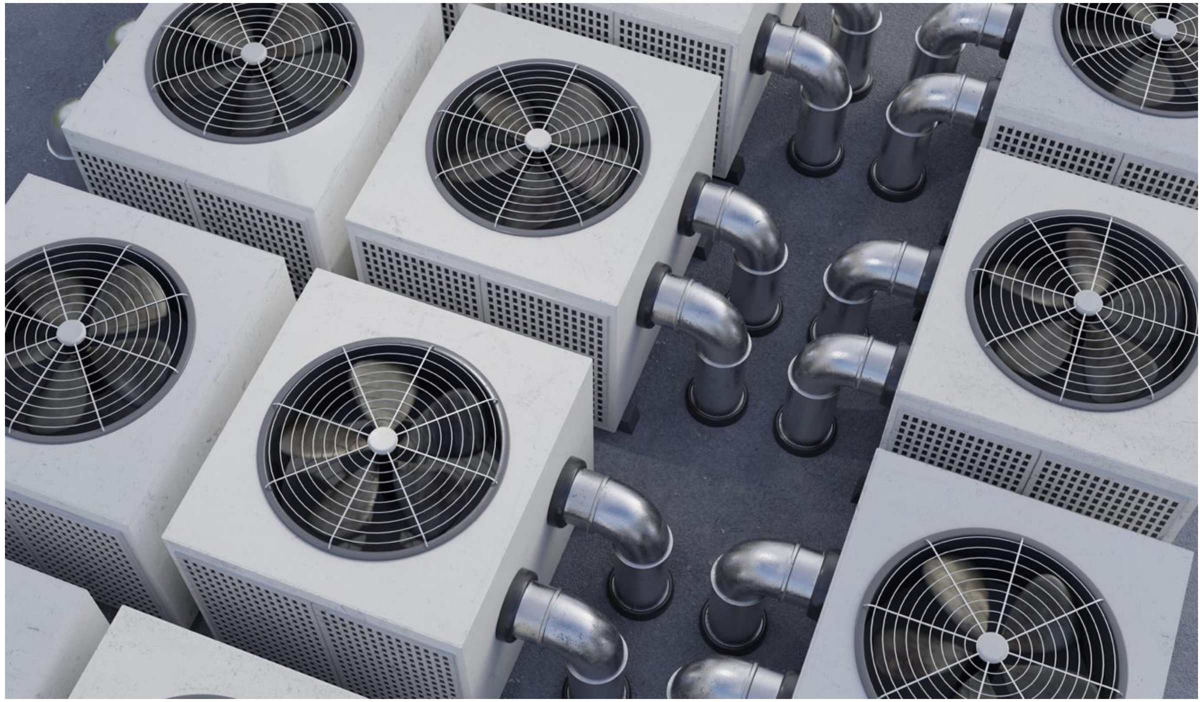


Image Source: vchalup – stock.adobe.com

MOFs can improve the efficiency of cooling systems in humid environments, in which traditional cooling is highly inefficient. An MOF with a high water vapor uptake can absorb the humidity from air and be regenerated, which would improve air conditioning efficiency by up to 30-50 % while producing freshwater[42] as a by-product (see air water generation section).

MIT-based startup, Transaera,[43] leverages MOFs in its advanced heat pumps systems to dehumidify the air before cooling, reducing energy demand by 40% per building. This cuts costs while also decreasing strain on the grid and the associated risks of power outages during extreme heat events.

MOFs: Resilience Applications

Food Supply Chain Resilience

MOFs also have emerging applications in protecting food supply chains. Many fruits and vegetables produce ethylene gas as they ripen, and this gas in turn accelerates ripening and spoilage in nearby produce. In supply chains disrupted by extreme weather, where transit times are longer and cold chain infrastructure may be damaged, this cascading spoilage effect is amplified. Rising ambient temperatures compound the problem since ethylene production and respiration rates in most fresh produce climb sharply with warmth, accelerating ripening and spoilage.[44]

Researchers have engineered MOFs that adsorb ethylene gas from the air surrounding stored produce, significantly extending shelf life[45] without requiring additional energy input. Recent experimental work has shown that removable MOF-based coatings applied directly to fruit surfaces[46] can combine ethylene capture with antimicrobial protection, markedly delaying spoilage. Someday, commercial MOF-based coatings or packaging could provide a lightweight, passive means of reducing food waste in storage and transit, particularly in regions where cold chain reliability is already limited and is worsening under climate stress.

Illustration of the preparation of MOF-based emulsions and their applications in the preservation of fruits

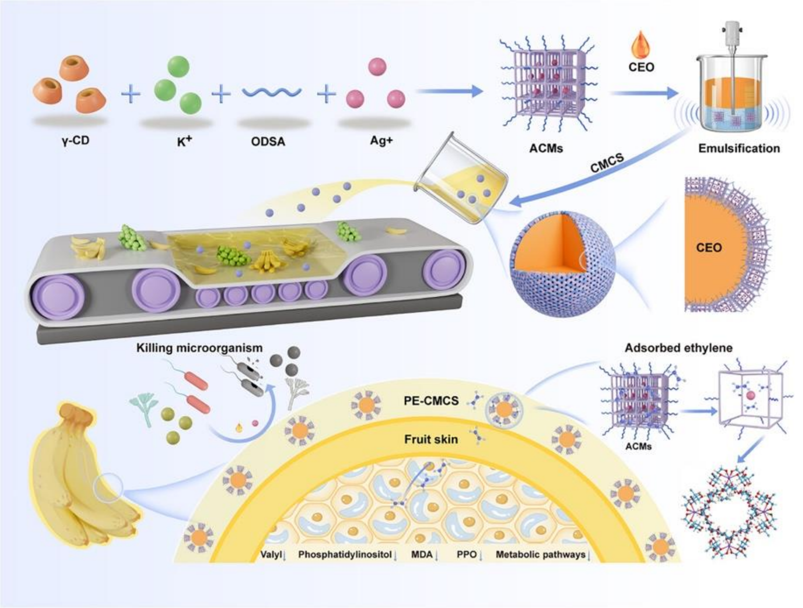


Figure source: Yang et al (2026)

MOFs: Maladaptation Risks

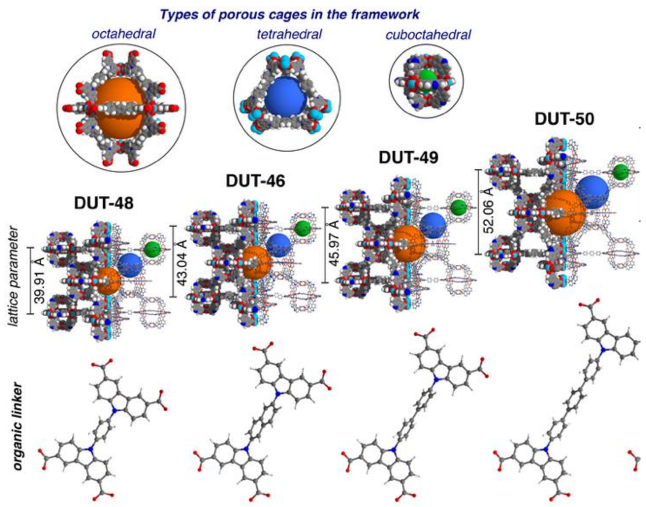
MOF-based AWG technologies, while more efficient than cooling-condensation systems, still require energy input, particularly in arid regions. There is a risk that these systems could be powered by hydrocarbon fuels, increasing emissions. However, it is more likely that AWG systems will be powered by waste heat from industrial processes that may be running on fossil fuels. There could be an opportunity to consider if using the waste heat contributes to the continuity of a fossil-fuel intensive operation and what the benefits and trade-offs are of this approach.

MOF manufacturing today carries its own environmental and health footprint. Metal precursors are typically drawn from conventional mining and refining supply chains, with zinc, aluminum, zirconium, copper, and iron among the most common. These carry the human rights and environmental risks associated with common approaches to obtaining these metals. Meanwhile, synthesis solvents such as N,N-dimethylformamide (DMF) are associated with occupational health risks, including liver toxicity, and manufacturing byproducts require careful handling and disposal. However, there are ways to mitigate this risk through alternative manufacturing processes that do not use DMF.

Early research on food-contact applications has demonstrated safety with MOF coatings that can be rinsed off fruit before consumption, for example. **Maintaining food safety at scale and developing intrinsically food-safe MOFs remains an active area of study.** Examining the environmental and human health risks from MOF supply chains and manufacturing, and identifying strategies to mitigate these risks will be an important element of the journey to scaling up commercialization of these technologies in a way that truly advances climate resilience.

MOFs: The Next Wave of Innovation

Materials



Adapted from Figure 1 in Krause et al (2019)
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Multiple research groups are pushing the frontier of MOF performance for water and environmental applications. At UC Berkeley, the Yaghi laboratory[47] continues to optimize MOF structures for atmospheric water harvesting, collaborating with Laura Gagliardi at the University of Chicago and Joachim Sauer at Humboldt University of Berlin to study water-framework interactions at the atomic level and design next-generation sorbents for arid environments. At MIT, the Device Research Laboratory[48] led by Evelyn Wang co-developed with UC Berkeley the first solar-powered MOF water harvester,[49] demonstrating practical water extraction from desert air in field trials in Arizona, and continues to advance scalable, solar-driven water harvesting devices for arid and water-stressed regions.

At Northwestern University, the Farha laboratory[50] does frontier work on per- and polyfluoroalkyl substances (PFAS), human-made "forever chemicals" that do not break down naturally. The group's MOFs capture PFAS[51] at record capacities and show potential to catalytically degrade them,[52] a step beyond activated carbon and other conventional adsorbents that can bind PFAS but not break them down. Meanwhile, researchers are examining the potential to use MOFs to recover critical minerals,[53] potentially providing a more resilient supply of these resources and an additional revenue stream from MOFs used for decontamination.

MOFs: The Next Wave of Innovation

Manufacturing

On the manufacturing side, the critical challenge is cost. MOF synthesis has historically relied on expensive precursors and energy-intensive batch processes. BASF[54] became the first company to produce MOFs at a scale of several hundred tonnes per year, and NuMat Technologies,[55] spun out of Omar Farha's lab at Northwestern, is now operating industrial-scale MOF manufacturing facilities in Chicago and Wisconsin. Part of the manufacturing challenge for MOFs is that they are often produced as powders which is not a useful form for most applications. Immaterial[56] addresses this by identifying specific MOFs to address clients' use cases and then manufacturing the MOFs in more directly usable form than powder. Several groups in the US and UK are exploring new synthesis methods aimed at bringing down production cost and time, including continuous-flow and aqueous processes that avoid the expensive solvents used in traditional batch synthesis. A 2025 study from Brookhaven National Laboratory and Lawrence Berkeley National Laboratory demonstrated a flame aerosol synthesis process[57] that produces MOFs in milliseconds rather than hours, pointing toward dramatically faster production at scale.

Illustration of MOFs produced by Numat

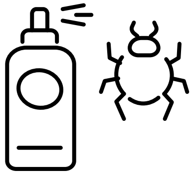
Image Source: Numat

Genomics & Gene Editing

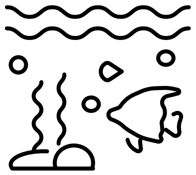
At a Glance

Genomics is the study of an organism’s entire genome and gene editing technology builds on this understanding to improve resilience outcomes.

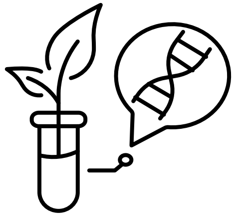
Ways genomics & gene editing can build climate resilience:



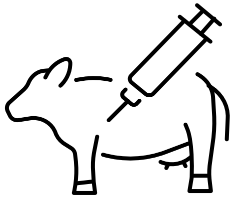
Reduce the spread of vector-borne disease



Reduce coral bleaching



Improve crop resilience to drought, heat and disease



Improve livestock resilience to drought, heat and disease

Example Startups:

- Avalo uses AI genomics modeling to breed for low-input, resilient crops.
- Agragene provides targeted pest control that reduces dependence on traditional pesticides.
- Biocentis produces sterile nonbiting male insect species to control pathogen hosts and agricultural pest populations.
- Coral Vita does high-tech land-based coral farming, using assisted evolution to select for resilient traits.
- InnerPlant engineers soy plants to provide signals when they’re infected with fungi.
- Pivot Bio develops nitrogen fixing microbes for crops to eliminate the need for chemical nitrogen fertilizer.

Genomics: The Technology

Gene sequencing, identifying the precise order of the four nucleotide bases in a segment of DNA, underpins the field of genomics. Sequencing genomes of individuals in a species paves the way for the development of a "reference genome,"[58] of that species, based on the genomes of several individuals in the population. This reference genome acts as a baseline for which to compare other genomes to understand why they may have different characteristics. This then allows genome wide association studies, where researchers compare healthy tissue to nearby tumor tissue for example, or thousands of people with a disease to thousands without, to identify which genes may be contributing to certain conditions.

In 1977 Frederick Sanger of Cambridge University sequenced a bacteriophage (a small virus that infects bacteria) genome, becoming the first to sequence a full genome. He shared half of the Nobel Prize in Chemistry 1980 with Walter Gilbert[59] for their work on nucleic acid sequencing. In 1988 the Department of Energy and the National Institute of Health launched the Human Genome Project[60] to coordinate international research efforts focused on sequencing the human genome as well as the genome of some nonhuman species. This initial sequencing took an international cohort 13 years and about $2.7 billion.[61] Meanwhile, the company Celera competed with the Human Genome Project, and added urgency to the public effort to produce genome information that was publicly accessible rather than patented. Both published initial drafts in 2001.

Today genome sequencing can happen in a few hours for a few hundred dollars, thanks to rapid research & development by universities and biotech companies in the late 1990s and early 2000s.

Gene Editing: The Technology

Illustration of the Cas9 gene cutting process

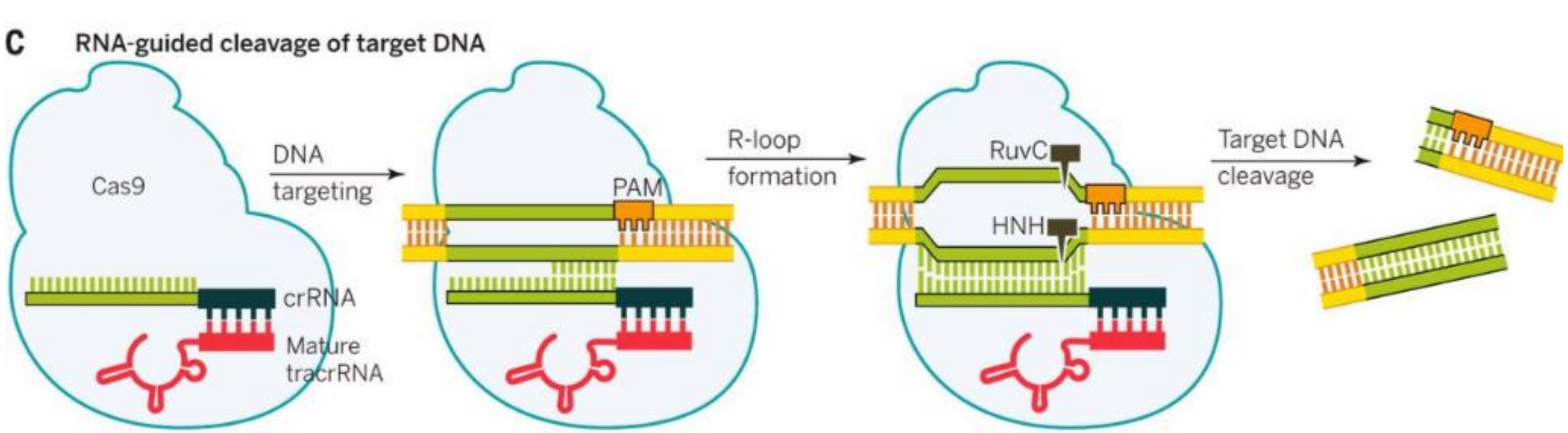


Image Source: Jennifer A. Doudna, Emmanuelle Charpentier (2014)

In 2012, Jennifer Doudna of UC Berkeley and Emmanuelle Charpentier published a paper with their collaborators that would earn them the Nobel Prize in Chemistry and transform the world of genomics. The paper, "A Programmable Dual-RNA-Guided DNA Endonuclease in Adaptive Bacterial Immunity"[62] announced their discovery[63] of the potential to use the CRISPR-Cas9 gene expression system to significantly improve the efficiency and efficacy of gene editing. Cas9 is a protein used by bacteria to seek intruding viral genes and destroy them. The researchers identified that Cas9 can be engineered to cut specific portions of DNA, guided by RNA. This unlocked a flurry of academic and commercial research examining the implications and ethical considerations of this discovery. Today many labs are examining new applications of the CRISPR-Cas9 gene editing system.

Genomics & Gene Editing: Resilience Applications

Vector-borne Disease Control: Sterile Male Approach

Image Source: panyawat – stock.adobe.com

Climate change is increasing the geographic range[64] of host species of many vector-borne diseases such as malaria, dengue and others. Researchers are using genomics[65] to better understand the host and disease relationship, transmission mechanisms, and opportunities to control populations and disease spread. **There are two main genomics-based approaches to control vector-borne disease: sterile male and gene drive**.

The sterile male approach has been around for decades, first conceptualized in the 1930s and 1940s[66] by separate research programs at Moscow State University, a field station in what is now Tanzania and the US Department of Agriculture.

The approach relies on releasing huge amounts of sterile males of the pest species mosquitos into the population, which means the females they breed with produce no offspring and populations gradually decline. This requires continued releases of many sterile males to effectively control the population. Sterilization was done with radiation before CRISPR was discovered and that is still the primary approach used in the field today.

Sterile male approaches are already on the market. Flyttr[67] (previously Oxitec) has been commercializing these approaches for over a decade.[68] Oxitec was originally founded in 2002 as a spinout from Oxford University and was acquired by Intrexon[69] (now Precigen) for $160 million in 2015. It has since grown into a global provider of next generation solutions to vector-borne disease, agricultural pests and invasive species.

Genomics & Gene Editing: Resilience Applications

Vector-borne Disease Control: Gene Drive Approach

The gene drive approach uses genetic systems known as "gene drives" that can spread themselves through target populations, thus reducing the need for mass-release. To be useful, these are connected to a trait that either reduces the mosquito's ability to host and transmit the pathogen, or reduces the mosquito's fertility. The gene is chosen and edited in such a way that inheritance is biased in its favor. Austin Burt at Imperial College was the first to propose that naturally occurring "selfish genes" could be harnessed to slow the spread of malaria in a 2003 paper[70], but work on this idea rapidly accelerated after the discovery of CRISPR. Researchers from Imperial College London outlined the first successful demonstration of this approach in a 2018 paper examining the population suppression of caged Anopheles gambiae mosquitoes.[71]

The downside of this approach is that it could spread rapidly through many populations across jurisdictional boundaries raising regulatory and ecological concerns. The benefit of the approach is that it relies on small releases with big impact. This means it would require less follow-up releases, which may also make it less commercially feasible. Researchers such as Luke Alphey at the University of York,[72] are examining options for an in-between approach that relies on the gene drive mechanism but restricts the geographic spread, allowing different communities to make different choices.

Genomics & Gene Editing: Resilience Applications

Reducing Volatility in Agriculture: Understanding Stress Tolerance

Genomics and gene editing have a range of applications in building resilience of crop and livestock production to changing temperature, shifting water availability and more widespread pests and disease. Selective breeding has been used in agriculture for thousands of years[73] to cultivate plant strains with desirable characteristics. However, it is traditionally limited by the time it takes for plants to grow and demonstrate their tolerance or vulnerability to stress (or another desirable trait). Stress-tolerance is controlled[74] by many interacting genes and also influenced by the interaction between the genotype and the environment, making breeding for climate resilience particularly challenging. However, sequencing a species' genome allows researchers to design experiments that identify which genes may be influencing certain characteristics. This allows breeders to selectively breed for these genes, accelerating the process and making it more precise.

The field has been defined by many breakthroughs identifying genes responsible for resistance or stress to certain conditions, such as salinity, submergence, drought, or heat, in specific crop species.

Image Source: JJ Gouin – stock.adobe.com

Genomics & Gene Editing: Resilience Applications

Reducing Volatility in Agriculture: Editing Genes to Improve Resilience

The CRISPR discovery provided a tool to help rapidly accelerate evolution that could occur naturally, by altering or removing genes that may be associated with higher stress. In the regulatory and research space this approach is distinct from genetically modified organisms (GMO), as it doesn't involve adding genes from other species, but simply editing within a species' genome. It tends to be faster,[75] less expensive and doesn't face the same regulatory labeling requirements as GMOs.

The first CRISPR edited food came to market in 2021 in Japan produced by Sanatech Seed. While this GABA-enriched tomato[76] and other early CRISPR edited crops were positioned as healthier or more appealing to consumers, climate-resilient crops and livestock is an area of rapid research and development. Researchers have used CRISPR to produce[77] drought resistant barley and potatoes, among others. Doudna's lab, in collaboration[78] with Brian Staskawicz at UC Berkeley, is researching opportunities to improve gene editing efficiency in plants, overcoming challenges presented by the cell wall.

The specificity of interventions based on certain species and traits means that the potential interventions are expansive but require ample research. This has opened the door for a range of companies focused on solutions for particular agricultural challenges. For example, InnerPlant, founded in Davis, CA in 2018, engineers crops to provide signals[79] when they're infected with fungi. Pivot Bio founded in San Francisco in 2010 and now worth an estimated $2B,[80] engineers nitrogen fixing microbes[81] to eliminate the need for chemical nitrogen fertilizer.

Companies are also applying the sterile male technology discussed above to develop agricultural pest control solutions. Agragene,[82] founded in St. Louis in 2017, is currently testing its sterile male Spotted Wing Drosophila produced using CRISPR to sell to berry farmers in the US and Canada where the flies cause up to $1 billion in damage annually.

Genomics & Gene Editing: Resilience Applications

Coral Bleaching

Image Source: Scuba Diver – stock.adobe.com

Coral reefs provide habitat for an estimated 25% of the world's marine life[83] despite covering only about 1% of the world's oceans. They underpin a large portion of the global food supplies, provide economic benefits from tourism and help buffer waves, reducing coastal flooding and erosion. However, coral bleaching, when the coral animal expels its algal symbiont, leading reefs to lose their color and the ecosystem they support, is increasing as ocean temperatures warm. From January 2023 through September 2025, an estimated 84.4%[84] of reefs experienced bleaching-level temperatures.

Over the past ten years, genome sequencing has improved[85] the field's understanding of the range of algal species that can be coral symbionts and subsequent research has identified which species have higher heat tolerance. Researchers at the Australian Institute of Marine Science and Hawaii Institute of Marine Biology first proposed using genetic modification to build the resilience of coral to extreme temperatures in a 2015 paper.[86]

In 2020, researchers[87] from Stanford, the Australian Institute of Marine Science and Queensland University of Technology used CRISPR to examine gene function and identify a gene that influences coral's heat tolerance for the first time. Startup Coral Vita[88] founded in 2017 grows resilient coral in land-based farms that can then be used to restore reefs.

Genomics & Gene Editing: Resilience Applications

Unlocking New Frontiers in Biomanufacturing

Biomanufacturing[89] uses biological systems, such as cells, plants or fungi, to create useful products. Early biomanufacturing approaches focused on pharmaceuticals, such as human insulin,[90] but recent innovations have been applied in several industries beyond medicine and food. For example, crude biodiesel waste can be transformed[91] into clean, usable oil; bioleaching[92] uses microbes to recover critical minerals from industrial waste; biodegradable consumer products provide[93] alternatives to single use plastics; and biocementation that makes stronger cement could evolve into self-healing materials. Meanwhile, future applications could include biodegradable and flexible electronic components.

While traditional approaches relied on fermentation,[94] gene editing has unlocked new approaches to engineering cells to produce desirable materials. Manufacturers can use gas waste streams[95] such as carbon dioxide and methane as feedstock, essentially transforming waste into usable biological materials. Biomanufacturing's use of natural processes makes it far less energy intensive[94] and enables more decentralized production capacity, less vulnerable to disruptions from a single event, compared to synthetic chemical manufacturing processes.

Biomanufacturing remains in the early stages of commercialization, with challenges related to regulatory and consumer acceptance, as well as scaling production capacity and improving efficiency and reducing costs of equipment needed for the complex, multistep process. However, costs and time requirements have been decreasing over the past few decades.

Genomics & Gene Editing: Maladaptation Risks

Interventions that leverage gene editing do hold maladaptation risks which can be mitigated with thoughtful approaches. For example, as discussed above, the release of pests engineered to pass along a gene that causes sterility, could rapidly spread across many pest populations and potentially have cascading impacts on biodiversity, in addition to its positive impacts on disease control.

When leveraging gene editing for conservation efforts, there is risk that the resulting populations may lack genetic diversity, particularly if they are a set of clones. This could create populations that are more resistant to the specific stress related to higher temperatures for example, but lack the genetic diversity to overcome other challenges that may arise, such as shifting acidity, pathogens etc. **Maintaining genetic diversity within engineered populations and considering potential long-term population genomic implications of adjusting populations is particularly important as it relates to both coral restoration and agricultural resilience.**

Meanwhile, there could also be concerns around **inhibiting systemic change**. For example, there may be areas in which switching to new crop species would be beneficial given changing climate conditions, but if farmers and communities focus on planting existing crops that are engineered for resilience to certain conditions, they may miss the opportunity to switch to a different crop that may be more holistically better suited for the new conditions.

Genomics & Gene Editing: The Next Wave of Innovation

Ongoing Investigation of the Genome

One area of innovation in this space is leveraging LLMs to rapidly identify desirable traits and inform assisted evolution. This further speeds up the rate of assisted evolution that genome sequencing already accelerated. In 2024 researchers from InstaDeep and Google Deepmind published an article "A foundational large language model for edible plant genomes," [96] announcing AgroNT,[97] a publicly available large language model trained on 48 plant genome species, primarily crops. Founded in 2020, Avalo leverages AI genomics[98] modeling to breed for low-input, resilient crops.

Image Source: chokniti – stock.adobe.com

For coral restoration, a growing field of research is examining the use of probiotics to improve the host coral's resistance to higher temperatures, which would in turn reduce the amount of corals experiencing bleaching events. A 2025 paper[99] from researchers at The Chinese University of Hong Kong, the University of Hong Kong, King Abdulla University of Science and Technology and University of Konstanz Germany examined the ability of different bacterial strains to persist in the population and to improve heat tolerance. The researchers identified a strain that reduced the impacts of a natural bleaching event observed during the eight-month field trial. Brooklyn, NY based Azul Bio[100] founded in 2023, develops and sells live biotherapeutics that can be applied to corals in the wild or aquariums to improve their resilience.

Genomics & Gene Editing: The Next Wave of Innovation

Addressing Regulatory Hurdles

Image Source: NINENII – stock.adobe.com

While academic research on climate-resilient crops has been abundant, **the path to commercialization is slowed by regulatory challenges and the reality of field testing**,[101] which is important both for research on agricultural scale viability and for public adoption, but is limited by an inconsistent global policy landscape related to testing gene edited crops.

Similarly for vector-borne disease and pest control, while ongoing research strives to hone the balance of meaningful impact with limiting geographic reach, gaining regulatory approvals and popular support remains a critical challenge. For example, the Agragene technology discussed above is currently under review[102] by the EPA and USDA, but does have field trials underway.

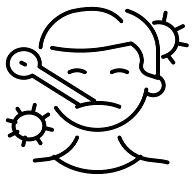
Genome sequencing has unlocked rapid increases in our understanding of the genetic drivers of many important traits, which has already led to new products and innovative solutions. Countless potential applications remain but those that leverage gene editing will continue to face regulatory and community headwinds in the near-term.

4D Printing

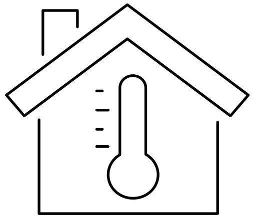
At a Glance

Four-dimensional printing (4D printing) combines additive manufacturing, also known as “3D printing,” with stimuli-responsive materials. This creates three-dimensional objects that morph into different forms in response to environmental stimuli, introducing the fourth dimension: time.

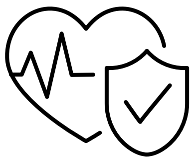
Ways 4D printing can build climate resilience:



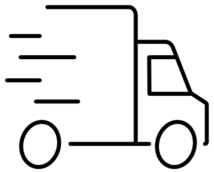
Reduce heat-related mortality and morbidity



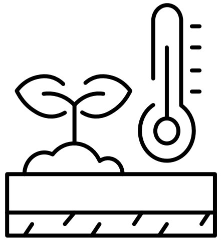
Increase resilience of buildings to extreme weather events



Support cardiovascular health



Reduce risks to food storage & distribution



Improve resilient agricultural practices

Example Startup:

- 4D Medicine (UK) is developing printable bioabsorbable medical devices

4D Printing: The Technology

Additive manufacturing, otherwise known as 3D printing, has been evolving for nearly 40 years[103] since its invention in the 1980s. Unlike traditional manufacturing, which is subtractive, involving cutting away material to achieve a shape, additive manufacturing builds structures by adding parts, often via the computer-programmed deposition of material in successive layers to create a three-dimensional object.

4D printing introduces a new dimension to additively manufactured products: time, specifically, the ability of an additively manufactured material to change shape in response to environmental stimuli (temperature, moisture, mechanical load, etc.) without power, sensors, or human intervention. The three key components of 4D printing include the additive manufacturing process, the stimuli-responsive materials, and the computational design to "program" the nature and sequence of the change.

Subtractive manufacturing (SM) vs additive manufacturing (AM).

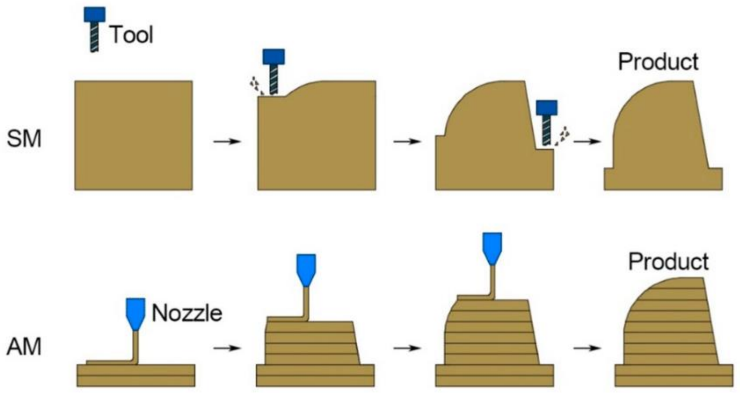


Figure Source: Tao et al (2020) Licensed under CC BY 4.0.

The concept of 4D printing was popularized by MIT researcher Skylar Tibbits in a 2013 TED talk,[104] in which he demonstrated a strand of printed material that folded itself into the letters "MIT" when submerged in water. The demonstration inspired a wave of academic research into how additive manufacturing could be combined with stimuli-responsive materials to create objects that transform over time.

4D Printing: The Technology

Additive Manufacturing Process

The printing process generally uses the same machine types as conventional 3D printing, with the additional requirement of multi-material printing capability.[105] Responsive materials are combined with non-responsive structural materials in a single print, with the geometry of their spatial arrangement determining how the finished object will change shape. Critically, printing parameters themselves such as nozzle path, speed, and layer orientation are active design variables rather than just process settings, because they directly govern how materials align and respond once printed. This makes 4D printing considerably more process-sensitive than standard additive manufacturing.

Computational Design

The computation design is a critical component of 4D printing, combining the structural needs of the item with the shape-change capability and utility. Traditionally, this required large amounts of iteration and testing, but advances in AI are introducing more rapid approaches to identifying optimal design.

Layering of different materials in 4D printed design

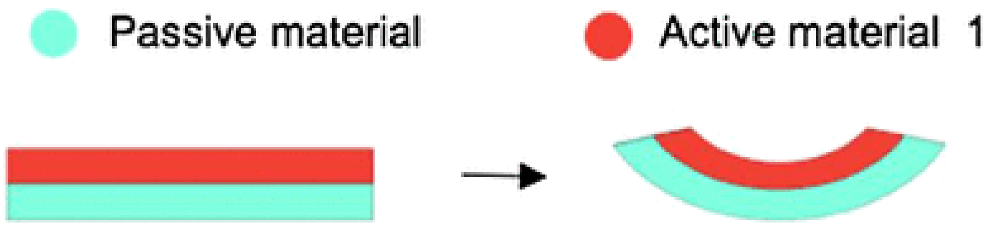


Figure Source: Pei, E and Loh G. H. (2018)

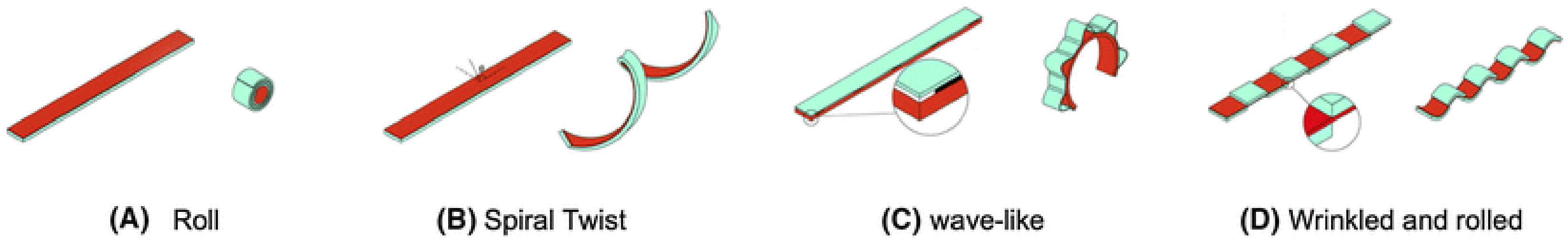
4D Printing: The Technology

Stimuli-responsive smart materials

Shape Memory Polymers

Shape memory polymers[106] (SMPs) are plastics that can be deformed into a temporary shape and then recover their original, "memorized" configuration when heated past a specific threshold temperature. The polymer's molecular structure is effectively frozen in a stressed state when cooled. Heating releases that stored tension and the material returns to its original form. The first journal publication on 4D printing of SMPs came in 2013 from H. Jerry Qi's group at the University of Colorado, which demonstrated that 3D-printed SMP structures could be programmed to self-fold into complex origami-like shapes when heated.

The main transformations of self-folding polymers



Source: Pei, E and Loh G. H. (2018)

4D Printing: The Technology

Stimuli-responsive smart materials

Hydrogels

Hydrogels[107] are soft polymer networks that swell to many times their dry volume when absorbing large amounts of water and contract as they lose moisture. Some also respond to temperature or acidity. Early water-responsive 4D printing, including Tibbits' original demonstration, relied on pairing materials that expanded at different rates to create hinge-like folds.

A landmark 2016 study from Jennifer Lewis's group at Harvard University and the Wyss Institute[108] demonstrated "biomimetic 4D printing,"[109] controlling the direction of swelling within the hydrogel itself. Hydrogel composites were printed with tiny embedded fibers arranged to mimic the internal structure of plant cell walls, controlling the direction and magnitude of swelling. These flat printed sheets curled and folded into precise three-dimensional shapes when placed in water.

Source: катя козлова - stock.adobe.com

Liquid Crystal Elastomers

Liquid crystal elastomers[110] (LCEs) are stretchy, rubber-like materials whose molecular building blocks naturally align in a common direction. When heated, this alignment becomes disordered and the material contracts, producing large (up to 55%), reversible shape changes. A 2015 study in Science[110] by researchers at the Air Force Research Laboratory, showed that this molecular alignment could be programmed to point in different directions in different zones of the same sheet, enabling flat LCE sheets to transform into precise, complex 3D shapes when heated. One of the authors, now at Texas A&M University, continues to advance programmable LCE systems for biomedical applications.

4D Printing: Resilience Applications

Improving outcomes for kidney disease patients during heat waves

One of the most promising applications of 4D printing in healthcare lies in the development of smart implants[111] that can release medication or change shape in response to specific internal body conditions, such as body temperature or pH shifts.

Many of the standard medications for chronic kidney disease patients, who face sharply elevated risk during heat waves,[112] can actually injure already-stressed kidneys when the body is dehydrated. Today's implantable drug delivery systems release medication at a predetermined rate regardless of what the body is experiencing. In 2023, researchers at the University of Texas at Austin demonstrated 4D-printed constructs[113] that self-fold at body temperature and modulate drug release as they change shape. This is a proof of concept for implants that could one day sense physiological stress signals such as shifts in body temperature or blood chemistry and automatically adjust medication dosing to match. This could prevent drug-induced kidney damage during extreme heat events.

Shape fixity and shape recovery process of potential d delivery construct: θ_{max} (maximum bending angle), θ_{fixed} (Fixed angle), and θ_i (Recovery angle)

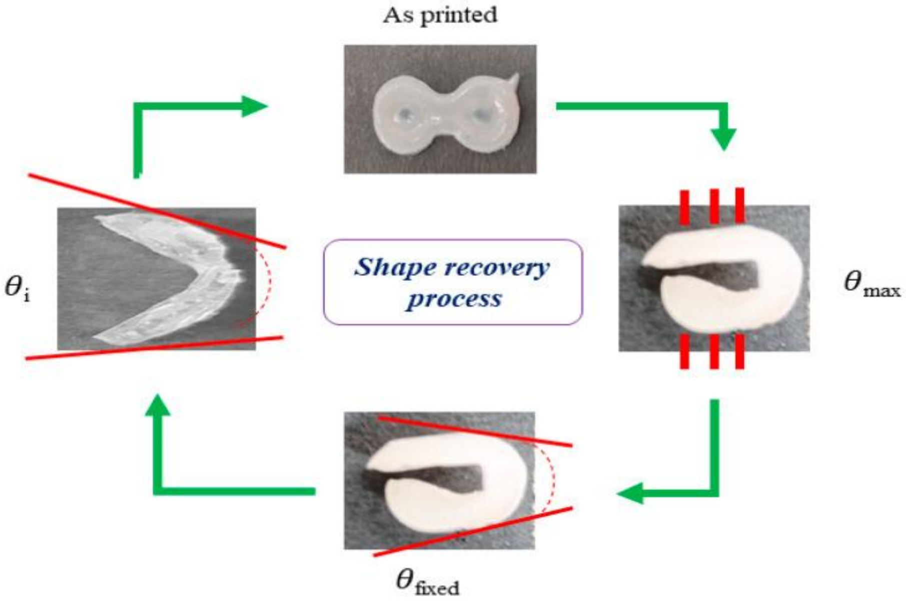


Figure Source: Suryavanshiet al (2023).

4D Printing: Resilience Applications

Improving cardiovascular outcomes with responsive implants

4D printed stent implantation

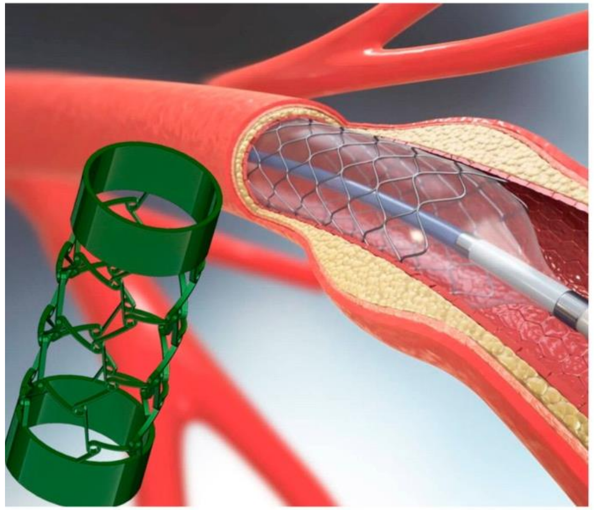


Figure Source: Kantaros, Petrescu, Ganetsos (2025). Licensed under CC BY 4.0.

Extreme heat forces the cardiovascular system to work much harder to cool the body, placing significant strain on patients with existing heart disease.[114] Today's vascular stents are small mesh tubes usually made from rigid metal expanded mechanically during surgery and inserted into arteries to hold them open. Once deployed, they remain fixed and cannot adapt to changes in the body.

Because blood vessels dilate and constrict under shifting thermal loads, a stent that could adjust its geometry alongside the vessel it supports would reduce strain on the artery wall, lowering the risk of blood clots and heart attacks. Researchers have recently demonstrated 4D-printed vascular stents[115] made from biodegradable shape memory polymers that self-expand gently at body temperature, offering a less invasive procedure. The biodegradability allows the stent to support the artery while it heals and then safely dissolve, avoiding the chronic inflammation that permanent metal stents can cause. As research progresses, there is potential for stents that continuously adapt to physiological changes, including the vascular strain from extreme heat.

These applications remain at the pre-clinical stage, with no 4D-printed medical device yet in human trials, but the pace of materials and printing advances suggests that gap is narrowing.

4D Printing: Resilience Applications

Improving Worker Safety and Food Storage in Agriculture

The ability to release nutrients, pesticides or preservatives in response to environmental conditions could reduce chemical overuse and extend the viability of food supply chains under climate stress. A 2025 study[116] demonstrated 4D-printed smart labels for fruit packaging that change both color and shape in response to humidity and CO_2 levels inside the package, simultaneously monitoring produce quality and releasing essential oils that slow spoilage.

Researchers have also demonstrated 4D-printed soft robots inspired by seed dispersal mechanisms[117] that self-burrow into soil in response to humidity. This could reduce agricultural workforce demands in extreme conditions and improve soil monitoring of agricultural land degraded by heat, drought or wildfire.

A 2022 review in Biotechnology Advances[118] identified a broad range of potential agricultural applications of 4D-printing, from controlled-release fertilizer systems to climate-responsive greenhouse covers, but noted that scholarly and industry attention in this area remains limited. These applications are at an earlier stage than the medical work described above, but they represent a plausible extension of the same core capabilities into an industry with clear climate risks.

Artificial seed self lifting (a) and moving up and down due to changing conditions (b)

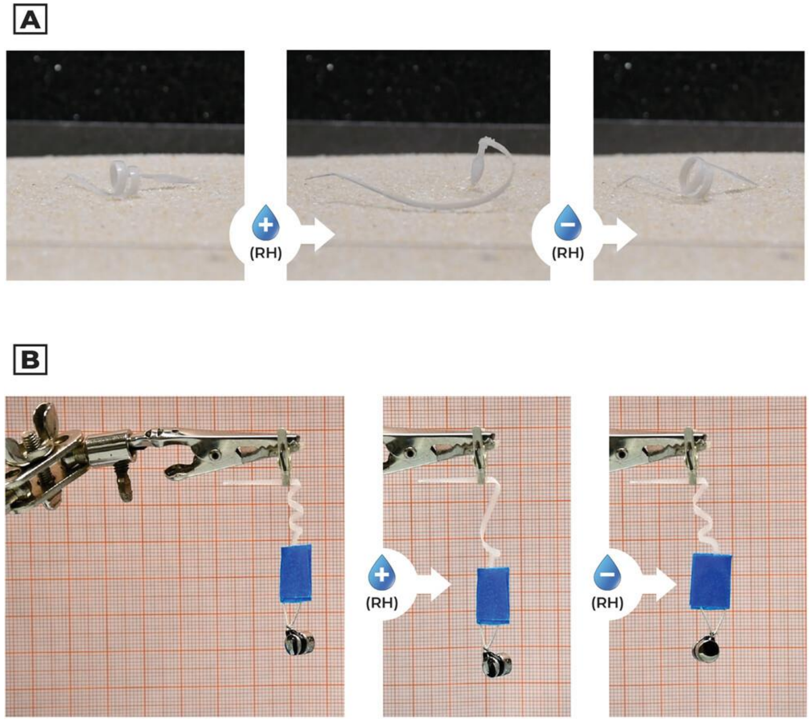


Figure Source: *Cecchini et al (2023)*

4D Printing: Resilience Applications

Adaptive Built Infrastructure

Since initially presented in Tibbits 2013 TED Talk, little progress has been made on adaptive built infrastructure. Outside of the US, some studies have demonstrated different dimensions of the opportunity in the space, but no area appears to have received consistent focus from researchers or funders to date. For example, a 2015 proof-of-concept at the University of Wollongong, Australia showed a 4D-printed valve that changed shape in response to water temperature[119] but had no apparent follow-up.

A 2024 study from the University of Stuttgart and the University of Freiburg,[120] Germany demonstrated 4D-printed building facade elements that autonomously shade occupants in response to humidity. That study's lead author, Tiffany Cheng, is now at Cornell continuing research on 4D printing, and has noted[121] the potential for commercial applications of these building materials.

4D printed adaptive shading system on a building façade

closed configuration (g)

open configuration (h)

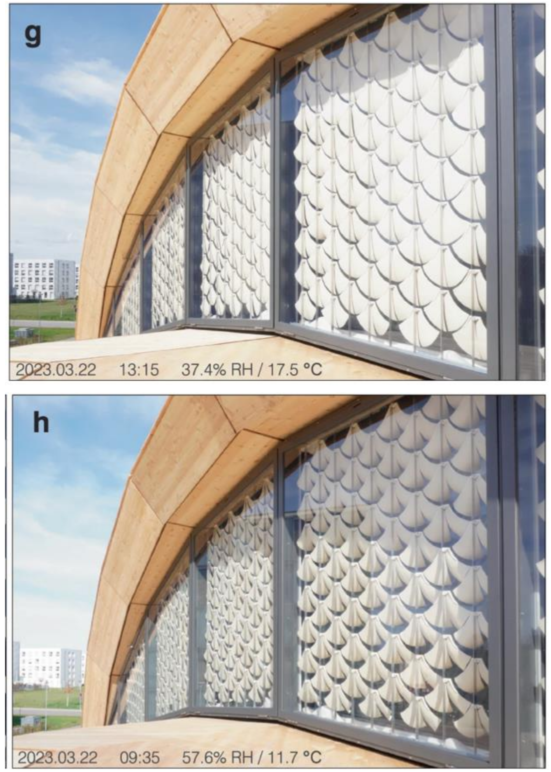


Figure source: Cheng, T., et al (2024)

Tailwind FUTURES

4D Printing: Maladaptation Risks

To date, the maladaptation risks associated with 4D-printed medical devices appear low. The technology is small in scale, does not carry a significant energy or emissions footprint, and its clinical applications are additive to existing treatment options rather than displacing them. At the individual level, patients with adaptive implants could develop a false sense of protection against extreme heat, reducing their adherence to behavioral precautions that remain essential.

At the systemic level, as with any medical intervention that reduces the health toll of extreme heat, care should be taken that improved clinical outcomes do not diminish urgency for heat mitigation measures such as workplace protections and urban cooling infrastructure. There is also the consideration of testing, which is relevant for any wearable or implanted device. Its effectiveness will be informed by the body types and conditions it was tested on, with implications for the equity and scope of its reach and positive impact.

Image source: Graphicroyalty – stock.adobe.com

4D Printing: The Next Wave of Innovation

Progress in transitioning 4D printing from proof of concept to commercial technology is happening across the printing process itself, the materials used and the computational tools required to design complex shape transformations.

Academic research articles on 3D and 4D printing over time

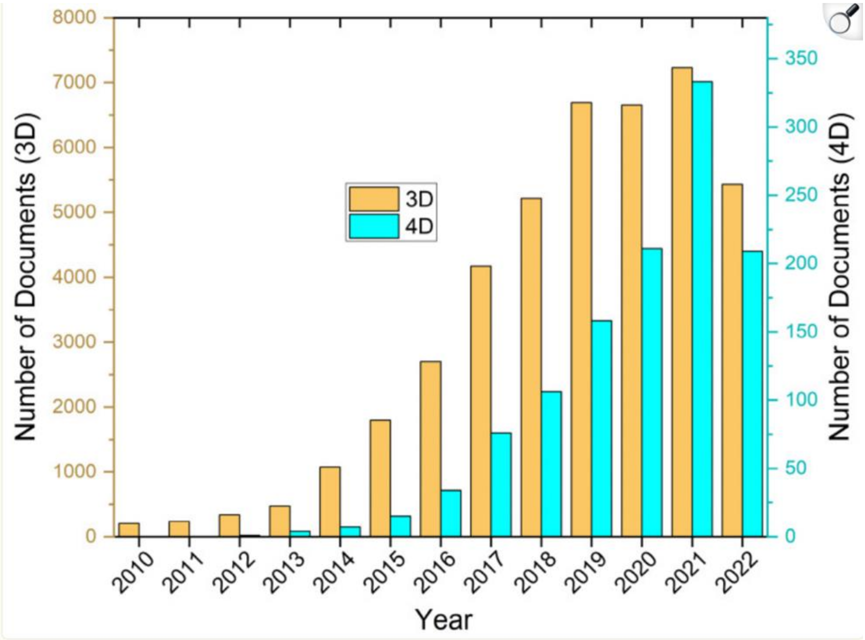


Figure source: Polymers (Basel). 2022 Nov 3;14(21):4698. doi: 10.3390/polym14214698

AI as An Enabler to Hard Tech Advancements

AI has emerged as a ubiquitous tool across industries. While this report focuses on the hard-tech research landscape and applications to A&R, it's worth noting that rapid advancements in AI have unlocked accelerated innovation in hard tech fields. From discovering new formulations of metal organic frameworks to identifying new printing patterns for shape memory polymers, researchers can now use AI to crank out hundreds of options for things that used to rely on repetitive and time-consuming trial and error. AI can also rapidly increase data analysis times. However, there is still a bottleneck when it comes to product testing, particularly for those solutions that require human testing, such as medicine, medical implants or wearables. For these products, the key bottleneck[122] is in regulatory approvals, recruiting participants and conducting clinical trials. Thus, while AI is already speeding up parts of the R&D process, the full road to commercialization will continue to be slowed down by the slowest stage related to product testing.

4D Printing: The Next Wave of Innovation

Deposition Process

Most 4D-printed structures have been produced using extrusion-based methods, similar to a hot glue gun depositing material through a nozzle. This limits how fine and complex a printed structure can be. In 2026, researchers at the University of Colorado Denver led by Martin Dunn and Kai Yu identified a new digital light processing approach[123] that uses projected light to cure entire layers of material at once, enabling much higher precision. Equally important, the desired shape transformation is programmed into the structure after printing in a separate step, rather than during the print itself. This separation of fabrication and programming opens the door to more practical manufacturing workflows.

Liquid crystal elastomer composite with different types of fiber reinforcements

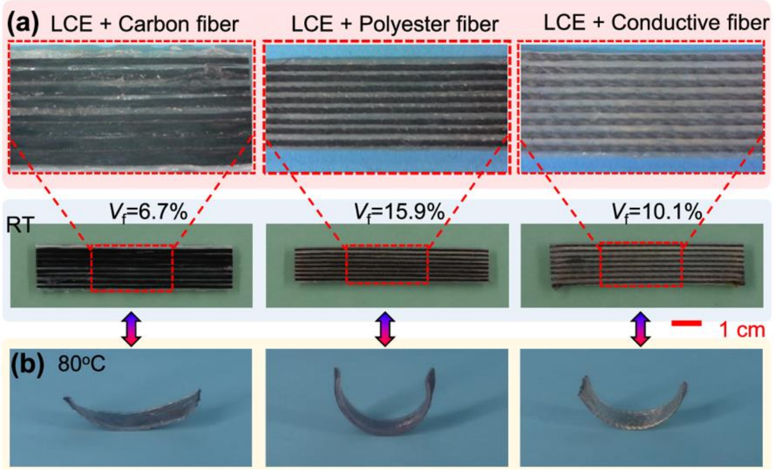


Figure source: Jiang et al (2024)

Materials

Among the materials used in 4D printing, liquid crystal elastomers are particularly promising for next-generation applications. Unlike shape memory polymers, which can typically only perform their shape change once before needing to be manually reset, liquid crystal elastomers can deform and recover repeatedly. In 2024 the same University of Colorado Denver group demonstrated[124] that weaving continuous reinforcing fibers through these materials during printing dramatically increases both the force they generate and their structural strength, producing a material capable of real-world applications rather than just laboratory demonstrations.

4D Printing: The Next Wave of Innovation

Computational Design

Figuring out exactly what arrangement of material to print to achieve a specific shape change is an enormous design challenge, with nearly infinite possible combinations. Instead of trying a design, seeing how it behaves, and iterating to get closer to an intended outcome, in 2024 H. Jerry Qi's lab at Georgia Tech demonstrated[125] a machine learning approach that works in reverse: a designer specifies the target shape, and the system determines the arrangement needed to achieve it. This removes one of the central bottlenecks that has kept 4D printing confined to research settings.

Schematic of a design process using machine learning

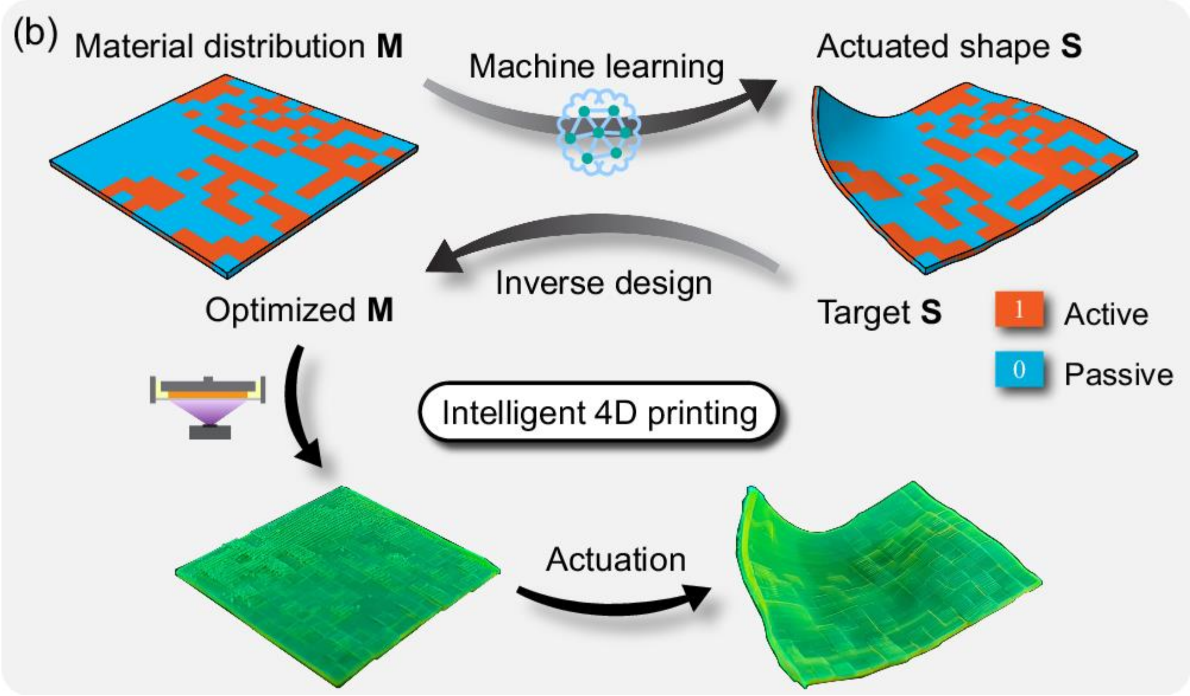


Figure source: Sun et al. (2024)

4D Printing: The Next Wave of Innovation

Reaching Commercial Scale

In terms of climate resilience, innovations in the printing process, the materials and the computational tools are converging most visibly in medicine, where 4D printing's ability to produce devices that respond to the body's own conditions without external control has clear value. While no 4D-printed medical device has yet entered human clinical trials, the field could be approaching this milestone. Though less directly related to resilience, there has been some traction in aerospace[126] applications for 4D printing where being able to omit the weight of the deployment mechanism for tools such as sensors or antennas has potential to improves mission efficiency.

While there is excitement for potential 4D printing applications across a range of industries, with various labs doing exploratory research, the primary focus of recent commercial traction has been on biomedical applications.[127] So far the economics of infrastructure do not[128] absorb the cost premium of smart materials as effectively as medicine does.

Electrically activated unfolding device

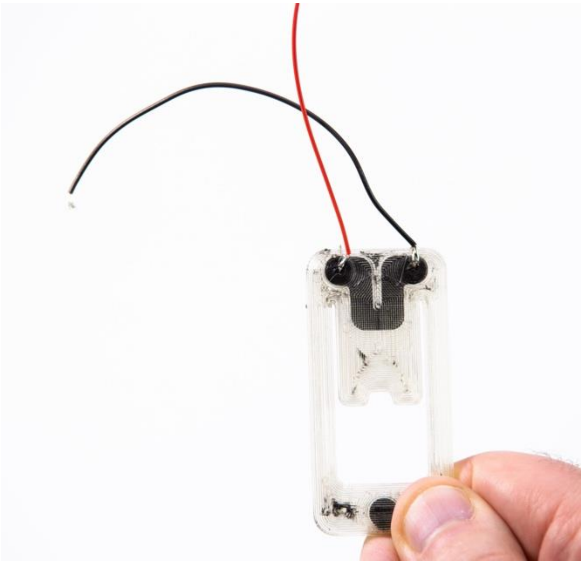


Image Source: Zortrax via 3DPrint.com

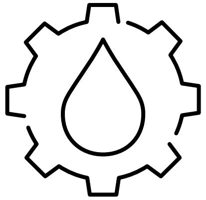
The costs of materials and printers, the need for reliable printers to print multiple materials, and the unknown integrity of many 4D printed items in the potentially harsh real-world conditions or at large infrastructure scales, remain important areas of further exploration[129] and research for this technology to scale into commercial products.

Solvent-Based Desalination

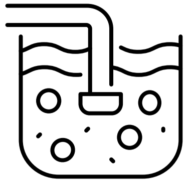
At a Glance

Solvent-based desalination uses liquids that bond with water molecules through chemical or physical interaction to pull water out of highly salty and contaminated brines, such as industrial wastewater.

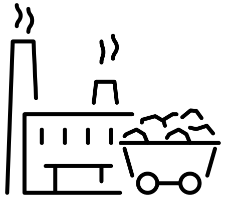
Ways solvent-based desalination builds climate resilience



Improve water circularity



Adapt to water table salination



Enable mineral extraction from waste brines

Example Startups:

- **Aquafortus** uses solvent extraction in combination with a membrane system to treat industrial brines.
- **Cetos Water** is commercializing temperature swing solvent extraction (TSSE) for ultra-high salinity brines.
- **Hydron Desalination** reduces water reuse cost by using solvent extraction and has a pilot ready for demonstration.
- **Trevi Systems** has licensed Idaho National Laboratory's dimethyl ether-based desalination work and deployed the first commercial pilot.

Solvent-based Desalination: The Technology

Solvent-based desalination uses liquids that bond with water molecules to pull the water out of highly salty and contaminated brines, such as those created by heavy industries. The solvent releases the water as a clean product when it's exposed to a change in temperature or pressure and then returns to the start of the cycle. The technology is quite different from the current best practices of reverse osmosis (RO) and evaporation, with the potential to complement or replace these techniques in some use case if energy requirements and efficiency can be optimized.

Osmotically assisted reverse osmosis (OARO)[130] has emerged as a potential approach to make reverse osmosis (RO) viable at higher salinities. While RO is the standard desalination approach, its reliance on membranes that foul at high salinity have made it impractical for industrial waste treatment. However, by keeping some salinity on both sides of the membrane OARO reduces the pressure required to push the water away from the highest salinity side, reducing the speed of membrane fouling. Hyrec opened the first commercial OARO plant in 2023[131] in Indonesia and produces water and food-grade salt, using both RO and OARO stages.

Today many brines that are too high salinity for RO are either disposed of or treated with multistage thermal evaporation[132] essentially boiling the water to remove contaminants and condensing the vapor into clean water. The multistage approach reuses heat from previous phases, making it much more efficient than single stage evaporation, but still energy intensive.

Solvent extraction has emerged as a potential alternative approach to high salinity water treatment that could benefit from not requiring a membrane and having different energy requirements than evaporative approaches.

Solvent-based Desalination: The Technology

Directional solvent extraction (DSE)

Solvent-based desalination has its roots in 1960s work at the U.S. Office of Saline Water. Richard Davison and Donald Hood's 1961 patent[133] described separating freshwater from brine using amine-based solvents. This approach became known as directional solvent extraction or temperature swing solvent extraction (since it relies on a temperature change). While there was a 1964 pilot plant[134] demonstrating potential commercial applications of the technology for seawater desalination, it didn't receive much focused research or commercial attention until recently. One reason is the solubility of amines in water. Some amine solvent is lost during each cycle, which has implications both for costs associated with solvent replacement and also contamination issues in the final clean water.

Given these limitations with amines, some research examined[135] the potential of using fatty acids as the solvent. However, the energy and equipment requirements[136] of this solvent were prohibitive given the huge amounts of solvent needed to take up comparable amounts of water.

Illustration of the desalination cycle using decanoic acid (a fatty acid)

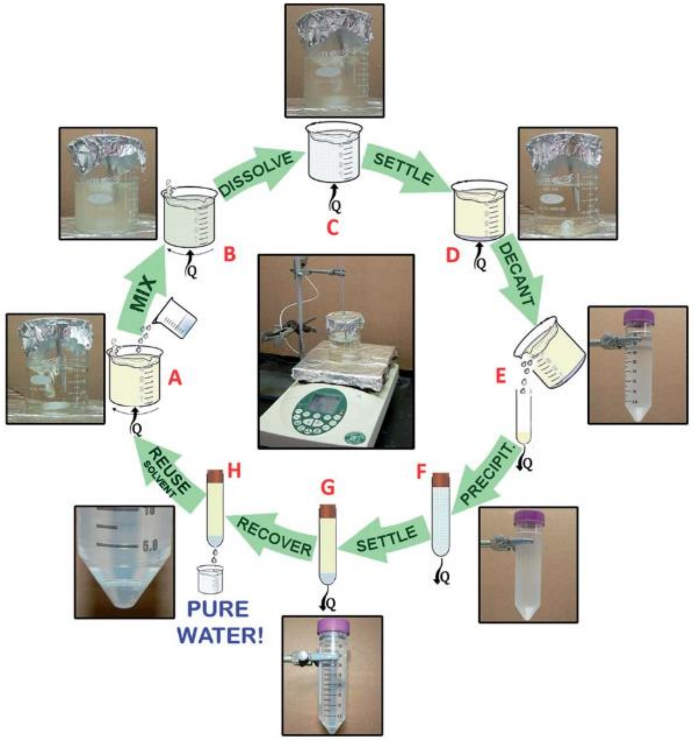


Image Source: Bajpayeeet al (2011)

Solvent-based Desalination: The Technology

Reaching zero liquid discharge unlocks mineral extraction as another product

Researchers at Columbia University[137] began examining the applications of directional solvent extraction for treating agricultural and industrial wastewater for reuse, where potable drinking water is not the end goal and the amine contamination is less problematic.

A 2020 paper[138] from the Yip Lab at Columbia demonstrated zero liquid discharge on a near-saturated salt brine (about eight times seawater salinity) of irrigation drainage water from California's San Joaquin Valley. This showed that directional solvent extraction could transform brine to dry solid salt, minerals, and cleaner water under real-world conditions, which presents the additional potential new use case focused on mineral extraction from brines.

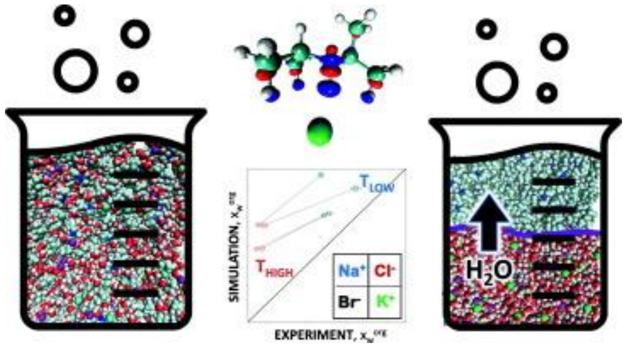


Figure source: Barbosa et al (2022)

Further research[139] from the Yip Lab and the University of Alabama, Tuscaloosa found that treatment efficiency varied based on the type of brine. Salt removal efficiency tends[140] to be based on the solvent used, while the amount of water recovered from the process is influenced by the mixing time, intensity and temperature, which all increase energy requirements. Ongoing research on these dynamics will be important to optimize trade-offs in real-world scenarios.

Solvent-based Desalination: The Technology

Dimethyl Ether (DME)

Dimethyl Ether (DME) is another solvent that can be used for extraction. Its use emerged in the 2010s out of Aaron Wilson's group[141] at Idaho National Laboratory with collaborators at MIT. DME is a gas at room temperature that liquefies at modest pressure. Liquefied DME absorbs water from brine while almost completely rejecting salt ions, then releases the water when the pressure is reduced and the DME returns back to a gas.

DME is best suited to applications where the brine is already under pressure from the extraction process itself, such as geothermal wells and oil and gas production. It is also suited to applications where water purity is a priority, since the phase change leaves essentially no solvent in the water. The trade-off is that all of the equipment must be rated for pressure, which raises capital costs.

Image source: Idaho National Laboratory

A 2024 paper in Industrial & Engineering Chemistry Research[142] from Idaho National Laboratory and MIT modeled an electric DME system with vapor compression for solvent recovery, indicating it could concentrate seawater brines all the way down to zero liquid discharge,[143] so every drop of water is recovered and only solid salt is left behind. The technology won a 2023 R&D 100 Award[144] and is being commercialized through a few early licensing partnerships.

Solvent-based Desalination: Resilience Applications

Enabling inland brackish groundwater desalination

California Pistachio Orchard

Image source: Dominic Genticore – stock.adobe.com

Unlike seawater RO desalination plants, which can release their ultra-saline concentrate back into the ocean (still constrained by environmental regulations[145]), inland groundwater plants have more limited and costly options. Underground injection sites are limited by geology and by tightening groundwater protection rules[146]. Surface discharge and evaporation ponds are also restricted.[147]

Converting a toxic liquid brine into a solid waste product, by running the desalination wastewater through solvent extraction systems, can reduce the volume of waste and may simplify the disposal process, since it tends to be easier to store solid waste[148] in leach-proof landfills. However, waste removal does remain a challenge that would be addressed by further improving approaches to process waste salt into usable mineral products.

Trevi Systems[149] is piloting a DME-and-reverse-osmosis plant at a pistachio orchard in California's Central Valley, converting brackish groundwater into irrigation water[150] and reducing the orchard's draw on the drought-stressed water resources. Trevi Systems notes that the resulting mineral biproduct could be used in the fields to reduce dust or sold for other uses. For this technology to be more widely adopted it will be important to verify real uses for the mineral biproduct or disposal approaches that work at scale.

Tailwind FUTURES

Solvent-based Desalination: Resilience Applications

Reducing the water draw of heavy industry

Extractive industries such as mining and oil & gas, as well as power generation, including natural gas, nuclear and newer approaches like green hydrogen, all consume large volumes of water for processing and cooling. As climate change reduces snowpack and aquifer recharge in the basins where these operations sit, they increasingly compete with municipal and agricultural users for a shrinking supply. These heavy industry operations often also produce hypersaline waste streams that historically have been challenging to dispose of and too salty for reuse or conventional treatment, leaving evaporation ponds[151] and injection deep underground[152] as the standard disposal approaches.

Solvent-based desalination has the potential to treat this waste, pulling out cleaner water that can be reused on site and therefore reducing the operation's draw on shared water resources. This lowers the company's exposure to operational disruptions, water-procurement related cost, and reputational risk in water-stressed regions.

Solvent-based desalination can also remove the trace toxic metals that contaminate mining brines. In 2024 the Yip Lab at Columbia demonstrated[153] removal of more than 99.5 percent of dissolved selenium and 96 to 99.6 percent of mercury, addressing salinity and contamination in one process. Cetos Water, the spinout from the Yip Lab's breakthroughs, won the 2025/2026 Future of Mining Challenge[154] from Wheaton Precious Metals for the technology's potential to convert mining wastewater into reusable water and recovered critical minerals. The award funds the company's first mining pilot.

Solvent-based Desalination: Maladaptation Risks

Water Contamination and GHG emissions

Several maladaptation risks deserve attention as solvent-based desalination scales, including the solvent (amine, ketones, ionic liquids etc) residue in the product water, the carbon footprint of the heat source, and the health and environmental impacts both of the salt waste and of industries the technology enables to continue operating in water-stressed regions.

As discussed above, amine-based TSSE solvents are partially soluble in water, so the product stream carries trace residue. The 2019 Yip Lab paper[137] showed that a low-pressure reverse osmosis polishing step (comparable in energy intensity to ordinary municipal water filtration) removes 96 to 98 percent of the residual amine.

Image source: agung – stock.adobe.com

If this final purifying step gets skipped or fails undetected, water contaminated with amines could potentially form carcinogenic compounds[155] in drinking water. Understanding the intended use of the water and ensuring that purification steps correspond to the purity required for that use will be essential to avoid any unintended negative health impacts. While the heat input for directional solvent extraction can come from renewable sources it can also come from burning hydrocarbons, which release greenhouse gases and contribute to climate change.

Solvent-based Desalination: Maladaptation Risks

Industrial Waste

The mineral waste resulting from solvent extraction still presents a toxic disposal challenge and potential environmental and health risks if not disposed of or recycled carefully. While ongoing research may improve opportunities to extract or reuse the mineral biproducts, many current practices still rely on hazardous waste disposal, which should be considered when planning a solvent extraction operation.

Treating hypersaline waste from oil and gas production or hard-rock mining helps those industries continue operating in places where water scarcity could otherwise affect project development. It also unlocks potential solutions and treatment opportunities for mining waste, which can have negative community impacts. When used intentionally this technology could help reduce contamination and improve water circularity in these industries. To minimize maladaptation risks it would be important to examine how the technology can be deployed to reduce adverse impacts on human and environmental health while also reducing the impacts of water scarcity on industry operations.

Image source: SoniaBonet – stock.adobe.com

Tailwind FUTURES

Solvent-based Desalination: The Next Wave of Innovation

Reducing Energy Requirements

Aquafortus Regeneration Tower

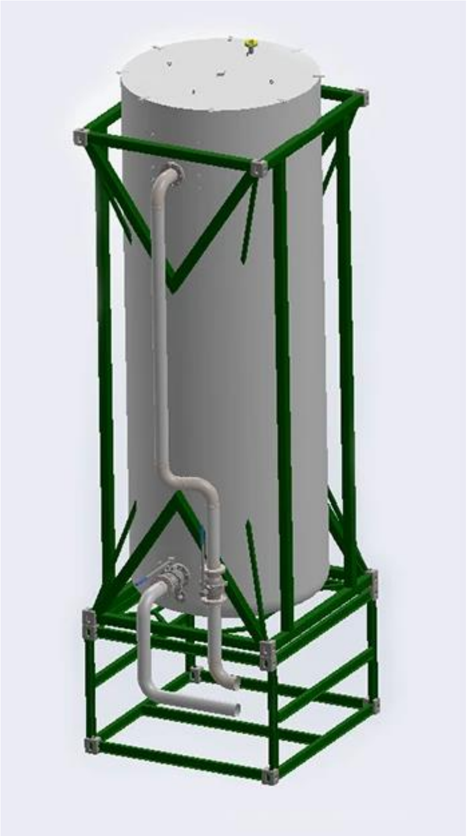


Image Source: Aquafortus

Ongoing academic research is expanding the range of brines solvent-based desalination can handle and the conditions under which it is economically viable to deploy. On the technical ability of the solvents themselves, the Yip Lab's 2023 computational screen of 60 amine candidates[156] and a 2025 paper[157] from Steven Weinman, C. Heath Turner, and Jason Bara's group at the University of Alabama maps solvents that leave less residue and work on harsher brines than the solvents used today. This includes oil sands tailings, landfill leachate, and acid rock drainage.

While the temperature change required for the solvent extraction is moderate, the energy requirements of bringing a large volume of solvent to the required temperature is still notable. The 2020 Yip paper estimates that current energy requirements are comparable to energy use of evaporative approaches discussed above, but potential minimum energy requirements are lower than minimum energy requirement of evaporative approaches. Further research identifying an optimal solvent composition will help to improve energy efficiency.

New Zealand-based startup Aquafortus,[158] with an operating facility in Texas, uses membrane-based approaches with solvent extraction, striving to minimize energy requirements by using each technology in the stage it is most optimized for.

Solvent-based Desalination: The Next Wave of Innovation

Ionic Liquid Solvents

Currently for amine-based solvent approaches the contamination with trace amines and the loss of some amine solvent presents both a challenge in terms of increasing operation costs due to resupplying the solvent, as well as environmental and human health concerns of the trace amines. The RO step discussed above adds logistics and equipment costs, complicating the utility of the solvent extraction for water that needs to be higher quality.

Early research is exploring the potential of ionic liquids as valuable solvent to balance energy costs, efficiency and contamination challenges. The diversity of ions means that there is opportunity to examine different ionic liquids to explore optimal formulations for different temperatures needs and salt concentrations.

Schematic of DSE using an ionic liquid as the solvent

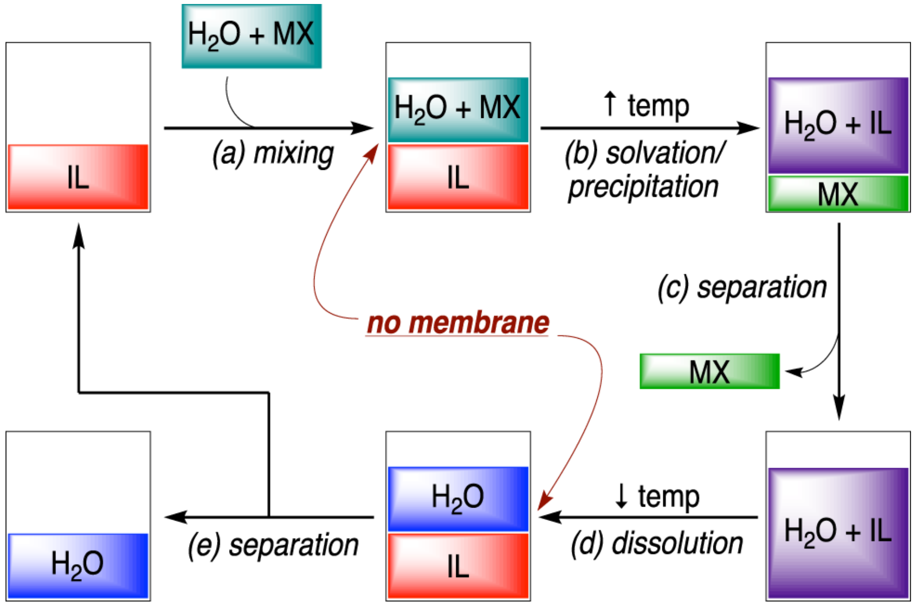


Figure Source: [Guo et al (2021)]

A [2021 Nature Communications study][159] from The Ashfeld and Luo labs at Notre Dame showed that an ionic liquid yields roughly ten times more water per cycle than decanoic acid, and ongoing research on this solvent may improve approaches that maintain the throughput provided by the amine solvents while avoiding the contamination issue. This ionic liquid solvent extraction technologically [underpins the pre-seed startup Solvion Engineering].[160]

AI-aided formulation could also help identify promising molecules to improve performance.

Solvent-based Desalination: The Next Wave of Innovation

Critical Mineral Recovery

Image source: Floren Horcajo – stock.adobe.com

Solvent extraction has been used to recover critical minerals[161] from mining, oil and gas wastewater, often in combination with other purification processes, and continued refinement of this approach, including honing the selectivity of solvents for specific minerals, could lead to potential revenue streams from the recovered critical minerals while also helping to address the challenges presented by the mineral waste.

Today, early commercialization pilots are beginning to demonstrate solvent extraction's ability to contribute to water purification processes and help to reduce water demands from agricultural and industrial users. These pilots use solvent extraction alongside traditional approaches such as RO, unlocking improved efficiency. They have yet to demonstrate that energy consumption is consistently lower than current approaches such as evaporation and OARO nor is there clear evidence on how cost-effective salt disposal is at scale compared to disposal of saline brines. However, ongoing research on recovering critical minerals from waste salt, and optimizing solvent construction could unlock efficiency gains and new revenue potential, helping position the technology as a key tool for industrial water resilience.

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