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Specialized toilet systems recover nitrogen and other nutrients from urine for use as fertilizers and other products.

HOW RECYCLING URINE COULD HELP SAVE THE WORLD

Separating pee from the rest of sewage could mitigate some difficult environmental problems and provide a sustainable source of fertilizer. But there are big obstacles to radically re-engineering one of the most basic aspects of life. **By Chelsea Wald**

On Gotland, the largest island in Sweden, fresh water is scarce. At the same time, residents are battling dangerous amounts of pollution from agriculture and sewer systems that causes harmful algal blooms in the surrounding Baltic Sea. These can kill fish and make people ill.

To help solve this set of environmental challenges, the island is pinning its hopes on a single, unlikely substance that connects them: human urine.

Starting in 2021, a team of researchers began collaborating with a local company that rents out portable toilets. The goal is to collect more than 70,000 litres of urine over 3 years from waterless urinals and specialized toilets at several locations during the booming summer tourist season. The team is from the Swedish University of Agricultural Sciences (SLU) in Uppsala, which has spun off a company called Sanitation360. Using a process that the researchers developed, they are drying the urine into concrete-like chunks that they hammer into a powder and press into fertilizer pellets that fit into standard farming equipment. A local farmer uses the fertilizer to grow barley that will go to a brewery to make ale — which, after consumption, could enter the cycle all over again.

The researchers aim to take urine reuse "beyond concept and into practice" on a large scale, says Prithvi Simha, a chemical-process engineer at the SLU and Sanitation360's chief technology officer. The aim is to provide a model that regions around the world could follow. "The ambition is that everyone, everywhere, does this practice."

The Gotland project is part of a wave of similar efforts worldwide to separate urine from the rest of sewage and to recycle it into products such as fertilizer. That practice, known as urine diversion, is being studied by groups in the United States, Australia, Switzerland, Ethiopia and South Africa, among other places.

The efforts reach far beyond the confines of university labs. Waterless urinals connect to basement treatment systems in offices in Oregon and the Netherlands. In Paris, there are plans to install urine-diverting toilets in a 1,000-resident eco-quarter being built in the 14th district of the city. The European Space Agency is to put 80 urine-diverting toilets into its Paris headquarters, which will begin operating later this year. According to proponents of urine diversion, it could see uses in sites from temporary military outposts to refugee encampments, rich urban centres and sprawling slums.

Scientists say that urine diversion would have huge environmental and public-health benefits if deployed on a large scale around the world. That's in part because urine is rich in nutrients that, instead of polluting water bodies, could go towards fertilizing crops or feed into industrial processes. According to Simha's estimates, humans produce enough urine to replace about one-quarter of current nitrogen and phosphorus fertilizers worldwide; it also contains potassium and many micronutrients. On top of that, not flushing urine down the drain could save vast amounts of water and reduce some of the strain on ageing and overloaded sewer systems.

Thanks to advances in toilets and urine-treatment strategies, many components of urine diversion could soon be ready for widespread roll-out, according to experts in the field. But there are also big obstacles to radically re-engineering one of the most basic aspects of life. Researchers and companies need to solve a number of problems, from improving the design of urine-diverting toilets to making it easier to treat urine and turn it into valuable products. This could involve chemical-treatment systems connected to individual toilets or basement devices that serve entire buildings, with pick-up and maintenance services for the resulting concentrated or solidified product. Then there are broader questions of social change and acceptance, related both to varying levels of cultural taboos around human waste and to deeply entrenched conventions about industrial sewage and food systems.

Urine diversion and reuse is the type of "drastic reimagining of how we do human sanitation" that will become increasingly crucial as societies battle shortages in energy, water and raw materials for agriculture and industry, says biologist Lynn Broaddus, a sustainability consultant in Minneapolis, Minnesota, who is former president of the Water Environment Federation in Alexandria, Virginia, an association of water-quality professionals worldwide. "The fact of the matter is, it's valuable stuff."

A new type of toilet

Urine used to be a valuable commodity. In the past, some societies used it for fertilizing crops, tanning leather, washing clothes and producing gunpowder. Then, in the late nineteenth and early twentieth century, the modern model of centralized sewage management arose in England and spread worldwide, ultimately leading to what has been called urine blindness.

In this model, flush toilets use water to quickly send urine, faeces and toilet paper into sewers, where it mixes with other liquids from households, industrial sources and sometimes storm run-off. At centralized treatment plants, an energy-intensive process uses microbes to clean the sewage.

Depending on local regulations and a treatment plant's condition, the wastewater discharged from the process can still contain a lot of nitrogen and other nutrients, as well as some other contaminants. And 57% of the world's population isn't connected to centralized sewer systems at all.

Scientists are working on ways to make centralized systems more sustainable and less polluting, but, beginning in Sweden in the 1990s, some researchers began pushing for more fundamental change. The end-of-pipe advances are "just, you know, another evolution of the same damn thing", says Nancy Love, an environmental engineer at the University of Michigan in Ann Arbor. Urine diversion would be "transformative", she says. In a study[1] that modelled wastewater-management systems in three US states, she and her colleagues compared conventional wastewater systems with hypothetical ones that divert urine and use the recovered nutrients to replace synthetic fertilizers. They projected that communities with urine diversion could lower their overall greenhouse-gas emissions by up to 47%, energy consumption by up to 41%, freshwater use by about half, and nutrient pollution from the wastewater by up to 64%, depending on the technologies used.

> **"We have really been stalled by this topic of toilets."**

Still, the concept has remained niche, mostly limited to off-grid locales such as northern European eco-villages, rural outhouses and development projects in low-income settings.

A lot of the lag is a result of the toilets themselves, says Tove Larsen, a chemical engineer at the Swiss Federal Institute of Aquatic Science and Technology (Eawag) in Dübendorf. First sold in the 1990s and 2000s, most urine-diverting toilets have a small basin at the front to capture the liquid — a set-up that requires careful aim. Other designs have incorporated foot-powered conveyor belts that let urine drain away while transporting the faeces to a composting vault, or sensors that operate valves to direct the urine to separate outlets.

But in European pilot and demonstration projects, people failed to embrace their use, Larsen says, complaining that they were too unwieldy, smelly and unreliable. "We have really been stalled by this topic of toilets."

These concerns plagued the first large-scale use of urine-diversion toilets — a project in the 2000s in South Africa's eThekwini municipality. After apartheid, the municipality's boundaries suddenly expanded, causing authorities to take over responsibility for some poor rural areas where there was no toilet infrastructure and little water service, says Anthony Odili, who researches sanitation governance at the University of KwaZulu-Natal in Durban.

After a cholera outbreak there in August 2000, the authorities quickly rolled out several types of sanitation that met financial and practical constraints, including about 80,000 urine-diversion dry toilets, most of which are still in use today. The urine drains below the toilet into the soil and the faeces falls into a vault, which, since 2016, the municipality has emptied every five years.

The project was successful at establishing safer sanitation in the region, Odili says. Social-science research, however, has revealed many problems with the programme. Although people felt that the toilets were better than nothing, Odili says, studies — including some he was involved in[2] — later found that users generally disliked them. Many had been constructed with poor materials and were awkward to use. Although such toilets should prevent bad odours in theory, urine in the eThekwini ones often entered the vaults with the faeces, causing a terrible stink. People were "not able to breathe properly", Odili says. What's more, the urine remains largely unused.

Ultimately, the decision to go with urine-diversion dry toilets, driven largely by public-health concerns, was top-down, and failed to take people's preferences into account, Odili says. A 2017 study[3] found that more than 95% of respondents in eThekwini aspired to the convenient, odourless flush toilets that wealthier white people use in the city — and that many have intentions to install them when their circumstances allow. In South Africa, toilets have long served as a symbol of racial disparity.

A new design, however, could represent a breakthrough for urine diversion. Led by designer Harald Gründl and in collaboration with Larsen and others, in 2017, the Austrian design firm EOOS (which has since spun off the company EOOS Next) unveiled the Urine Trap. This removes the need for users to aim, and the urine-diverting function is almost invisible.

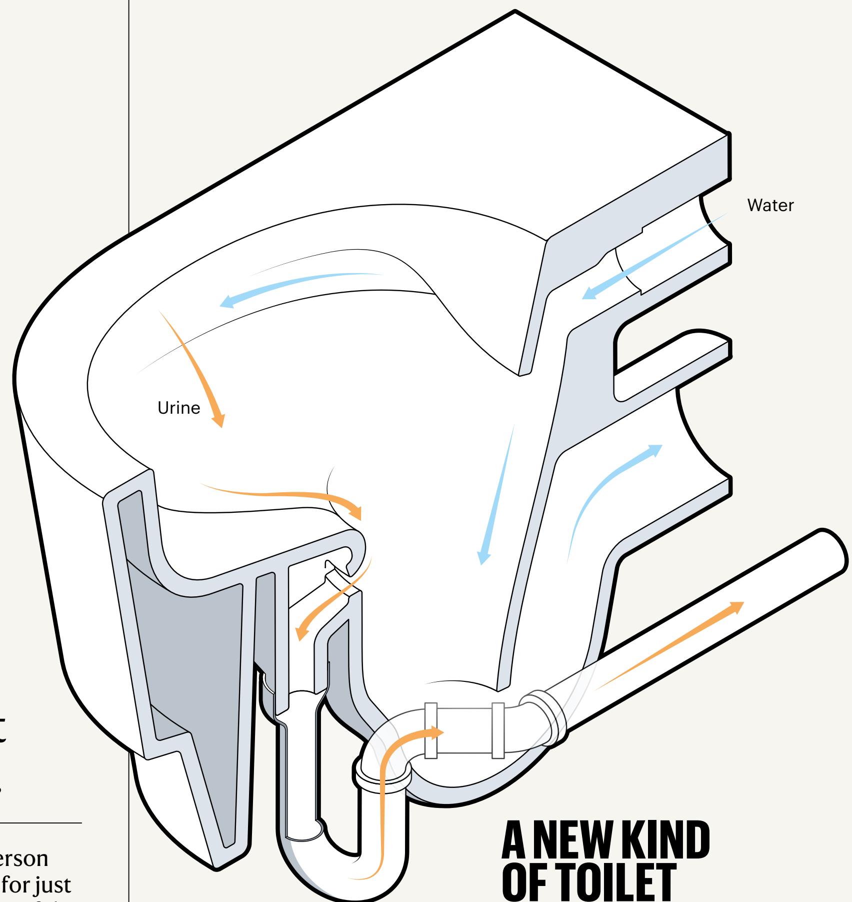
It takes advantage of water's tendency to cling to surfaces (known as the teapot effect because it's like an inconveniently dribbling teapot) to direct urine down the front inner side of the toilet into a separate hole (see 'How to recycle pee'). Developed with funding from the Bill & Melinda Gates Foundation in Seattle, Washington, which has supported a broad swathe of research into toilet innovation for low-income settings, the Urine Trap can be incorporated into everything from high-end

HOW TO RECYCLE PEE

Every toilet flush sends valuable nitrogen and other fertilizers down the pipes. Here's how to recapture some of the lost resources in human urine.

Urine is valuable stuff, and there's a lot of it. Each person produces about 500 litres per year. Urine accounts for just 1% of household waste water, but it contains 80–90% of the nitrogen, and at least half of the phosphorus and potassium, according to some studies. As the human population soars and the need for fertilizers continues to rise, recycling pee might be the best option — and it would stop some of those nutrients polluting waterways. Some communities are leading the way by installing specialized toilets and recycling urine.

By Richard Monastersky and Chelsea Wald
Design by Jasiek Krzysztofiak



A NEW KIND OF TOILET

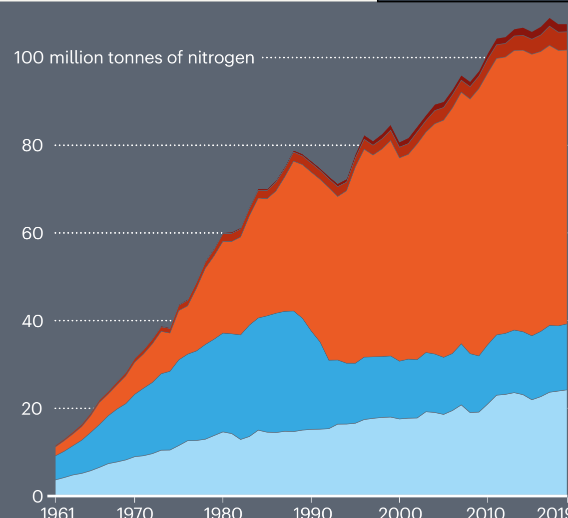
The key to recovering nutrients from urine is to separate it from the rest of the waste stream — a process called urine diversion (UD). UD systems range from those that process urine and faeces on the spot, to those that connect to larger sewage systems. In the Urine Trap design by Austrian firm EOOS, urine runs down the front of the bowl and over a lip into a separate pipe.

THE URINE PROBLEM

Nitrogen demand

The amount of nitrogen fertilizer used in agriculture has climbed to more than 8 times what it was 60 years ago. Much of it is produced using an energy-intensive process that relies on fossil fuels.

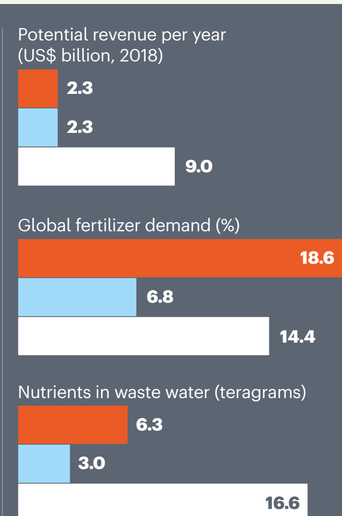
- Oceania
- Africa
- Asia
- Europe
- Americas



What's in urine

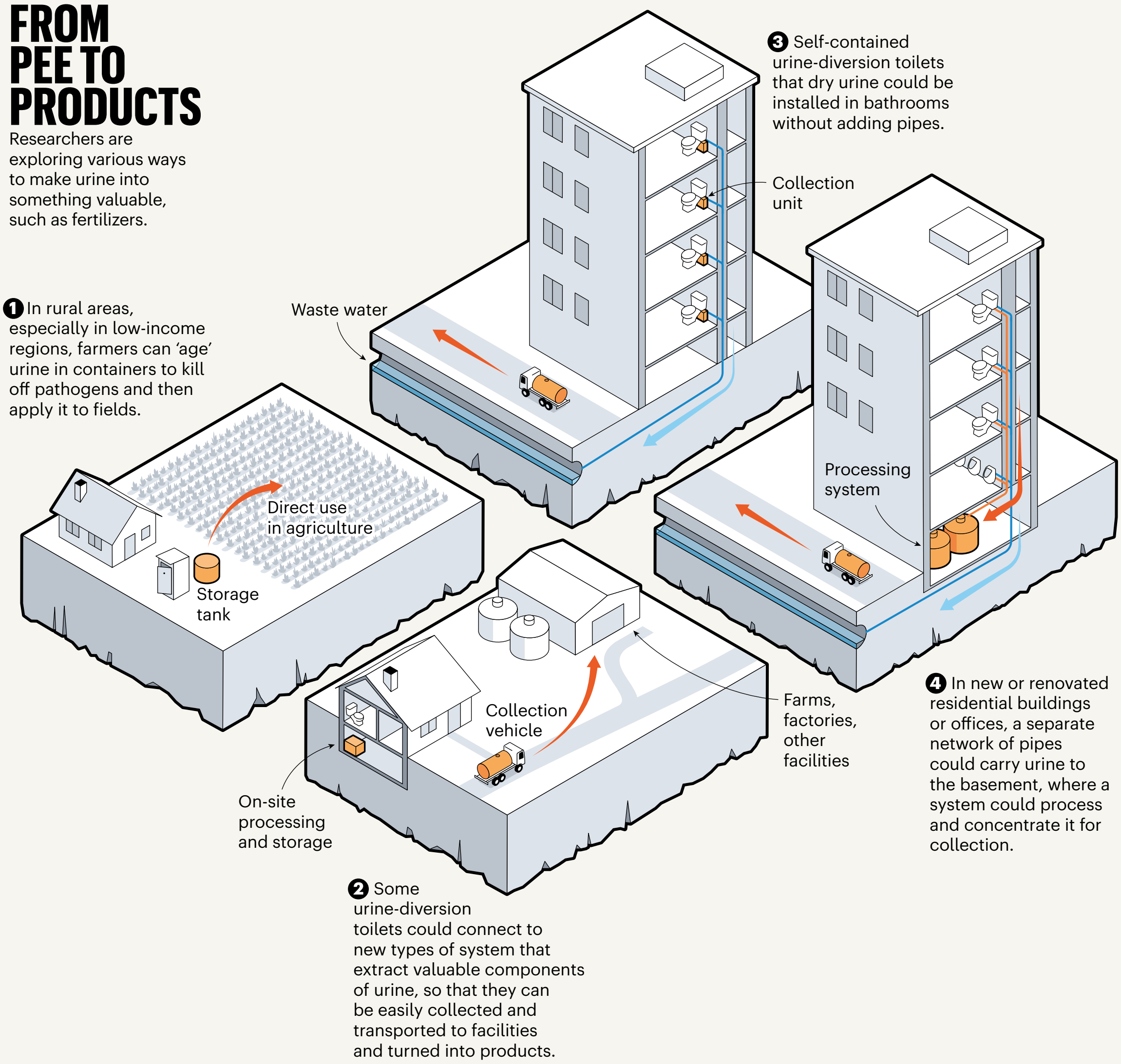
A study of urban waste water globally suggests it holds enough nitrogen, phosphorus and potassium to offset more than 13% of the agricultural fertilizer demand. The value of those recovered nutrients would equal US$13.6 billion annually.

- Potassium
- Phosphorus
- Nitrogen

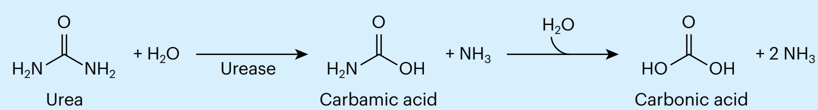


FROM PEE TO PRODUCTS

Researchers are exploring various ways to make urine into something valuable, such as fertilizers.

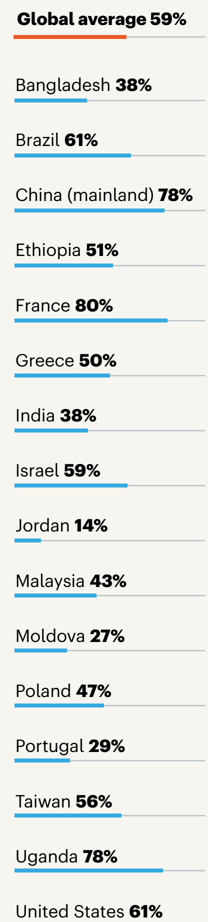


The urease enzyme catalyses a rapid reaction that turns urea in urine into ammonia, which smells. Many urine-diversion systems inhibit that reaction.



WILL PEOPLE EAT IT?

In a survey of more than 3,700 people at universities in 16 countries or regions, 59% said they would eat food fertilized by urine, but there was a wide range of acceptance.

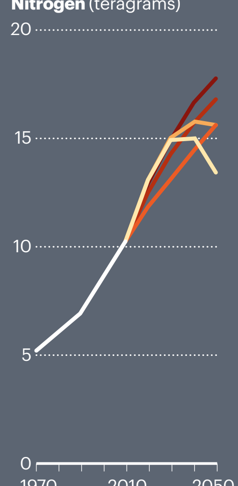


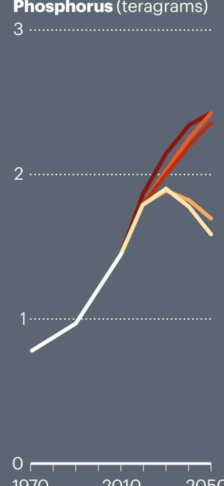
Future pollution

The amount of nitrogen and phosphorus pollution that goes into surface waters climbs rapidly in a modelling study that explores future scenarios called Shared Socioeconomic Pathways (SSPs).

SSP scenarios:

- 1 Slow green shift
- 2 Middle of the road
- 3 Fragmented world
- 4 Inequality gaps widen
- 5 Innovation and sustainability





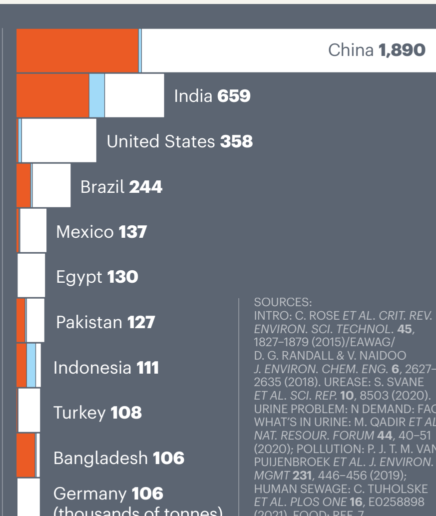
Human sewage

A modelling study suggests waste water adds 6.2 million tonnes of nitrogen to coastal waters around the globe. Here are the top polluters.

Sources of wastewater nitrogen that enters coastal* waters:

- No or very poor toilet facilities
- Septic tanks
- Sewers with treatment

*A country's exclusive economic zone.



SOURCES:
INTRO: C. ROSE *ET AL. CRIT. REV. ENVIRON. SCI. TECHNOL.* **45**, 1827–1879 (2015)/EAWAG/ D. G. RANDALL & V. NAIDOO *J. ENVIRON. CHEM. ENG.* **6**, 2627–2635 (2018). UREASE: S. SVANE *ET AL. SCI. REP.* **10**, 8503 (2020). URINE PROBLEM: N DEMAND: FAO; WHAT'S IN URINE: M. QADIR *ET AL. NAT. RESOUR. FORUM* **44**, 40–51 (2020); POLLUTION: P. J. T. M. VAN PUIJENBROEK *ET AL. J. ENVIRON. MGMT* **231**, 446–456 (2019); HUMAN SEWAGE: C. TUHOLSKE *ET AL. PLOS ONE* **16**, E0258898 (2021). FOOD: REF. 7.

ceramic pedestal models to plastic squat pans. LAUFEN, a manufacturer headquartered in Switzerland, is already producing one for the European market, called save!, although it is too costly for many consumers.

The University of KwaZulu-Natal and the eThekwini municipality have also been testing versions of Urine Trap toilets that divert the urine and flush the solids. This time, the research is more focused on the user. Odili is optimistic that people will prefer the new urine-diversion toilets because they smell better and are easier to use, but he points out that men would have to sit down to urinate, which is a big cultural shift. But if the toilet is "also adopted and accepted in high-income areas — people from different racial groups here — it really will help in the roll-out", he says. "We must always put on that racial lens," he adds, to ensure that they're not developing something that will be seen as 'just for Black people' or 'just for poor people'.

Uses for urine

Separating urine is just the first step in transforming sanitation. The next part is working out what to do with it. In rural areas, people could store it in vats to kill any pathogens and then apply it to fields. The World Health Organization provides guidelines for this practice.

But urban settings are trickier — and that's where most urine is produced. It's not practical to add a separate set of sewer pipes throughout a city to move urine to a central location. And because urine is about 95% water, it is too expensive to store and transport. So researchers are focusing on drying, concentrating or otherwise extracting nutrients from urine at the toilet or building level, leaving the water behind.

This isn't easy, says Larsen. From an engineering perspective, "urine is a nasty solution", she says. Aside from water, the largest portion is urea, a nitrogen-rich compound that bodies produce as a by-product of metabolizing proteins. Urea by itself is useful: a synthetic version is a common nitrogen fertilizer. But it's also tricky: when combined with water, the urea transforms into ammonia gas, which helps to give urine its characteristic scent. If not contained, the ammonia stinks, pollutes the air and carries valuable nitrogen away. Catalysed by the widespread enzyme urease, this reaction, called urea hydrolysis, can take microseconds, making urease one of the most efficient enzymes known[4].

Some approaches allow the hydrolysis to go ahead. Researchers at Eawag have developed an advanced process for turning hydrolysed urine into a concentrated nutrient solution. First, in a tank, microorganisms transform the volatile ammonia into non-volatile ammonium nitrate, which is a common fertilizer. Then a distiller concentrates the liquid. A spin-off company called Vuna, also in Dübendorf, is working to commercialize both the system for use in buildings and the product, called Aurin, which has been approved in Switzerland for use on edible plants — a world first.

Others try to stop the hydrolysis reaction by quickly raising or lowering the pH of the urine, which is usually neutral when it comes out of the body. On campus at the University of Michigan, a collaboration between Love and the non-profit Rich Earth Institute in Brattleboro, Vermont, is developing a system for buildings that squirts liquid citric acid down the pipes of a urine-diverting toilet and a waterless urinal. It then concentrates the urine through repeated freezing and thawing[5].

The SLU team doing the project on Gotland island, led by environmental engineer Björn Vinnerås, has worked out how to dry urine into a solid urea mixed with the other nutrients. The team is evaluating its latest prototype, a self-contained toilet including a built-in dryer, at the head office of the Swedish public water and wastewater utility VA SYD in Malmö.

Other methods target individual nutrients from urine. These could more easily slot into existing supply chains for fertilizers and industrial chemicals, says chemical engineer William Tarpeh, a former postdoc of Love's who is now at Stanford University in California.

One well-established way of recovering phosphorus from hydrolysed urine is to add magnesium, which causes the precipitation of a fertilizer called struvite. And Tarpeh is experimenting with beads of adsorption materials that selectively pluck out nitrogen in the form of ammonia[6] or phosphorus in the form of phosphate. His system uses another liquid, called a regenerant, to flow over the beads after they are spent. The regenerant carries off the nutrients and renews the beads for another round. It's a low-tech, passive method, but the commercial regenerants are environmentally damaging. His team is now trying to make ones that are cheaper and more environmentally friendly.

> **"When I think about the big future of urine recovery, we want to be able to make as many products as possible."**

Other researchers are developing ways to produce electricity by putting urine into microbial fuel cells. In Cape Town, South Africa, another team has developed a method for making an unconventional construction brick by combining urine, sand and urease-producing bacteria in a mould; these calcify into any shape without the need for firing. And the European Space Agency is eyeing astronaut urine as a resource for building habitats on the Moon.

"When I think about the big future of urine recovery and wastewater recovery, we want to be able to make as many products as possible," Tarpeh says.

As researchers pursue a slew of ideas to turn urine into commodities, they know it's an uphill battle, particularly with entrenched industries. Fertilizer and food companies, farmers, toilet manufacturers and regulators are slow to make big changes to their practices. "There's quite a lot of inertia," says Simha.

At the University of California, Berkeley, for example, a research and education installation of the LAUFEN save! toilet, including a drainpipe to a storage tank on the floor below, has unexpectedly taken nearly three years and cost more than US$50,000. That includes fees for architects, construction and complying with municipal codes, says environmental engineer Kevin Orner, now at West Virginia University in Morgantown — and it's still not done. The lack of existing codes and regulations has caused troubles with facilities management, he says, which is why he is on a panel that is developing new codes.

Some of the inertia might be due to concerns over customer resistance, but a 2021 survey of people in 16 countries or regions[7] indicated that willingness to consume urine-fertilized food approached 80% in places such as France, China and Uganda.

Pam Elardo, who leads the Bureau of Wastewater Treatment as a deputy commissioner in the New York City Department of Environmental Protection, says she supports innovations such as urine diversion, because further reducing pollution and recovering resources are key goals for her utility. The most practical and cost-effective approach to urine diversion for a city such as New York, she foresees, would be off-grid systems for renovated or new buildings, supported by maintenance and collection operations. If innovators can work that out, she says, "they should go for it".

Given the advances, Larsen predicts that mass production and automation of urine-diversion technologies could be around the corner. And that would improve the business cases for this transformation in dealing with waste. Urine diversion "is the right technology", she says. "It's the only technology which can solve the problem of nutrients from households in a reasonable time. But people have to dare."

Chelsea Wald is a freelance reporter in The Hague, the Netherlands, and the author of *Pipe Dreams: The Urgent Global Quest to Transform the Toilet.*

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