Microbes for better sewage treatment

Going beyond conventional approaches, researchers are using carefully cultured bacterial communities to improve sewage treatment—and create useful products in the process

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When it comes to the murky-looking water tanks in Kartik Chandran’s laboratory, fume hoods are essential. Not only do the tanks get regular top-ups of sewage sludge and food waste from a nearby cafeteria, but the microbial colonies inside can give off butyric acid—the distilled essence of sour milk and rancid butter. The tanks also emit an occasional whiff of hydrogen sulfide, says Chandran, which reeks of rotten eggs “till the senses are numbed.”

But then, says Chandran, an environmental engineer at Columbia University in New York City, the smell is just a sign that the microbes in the tanks are doing their job—namely, to revolutionize the way humans handle that inescapable stuff flowing into urban sewage systems, rural septic tanks, and countless lakes and rivers.

“It’s not waste water,” Chandran insists. But today’s water treatment plants typically handle it that way: Anything that’s not H₂O gets turned into carbon dioxide that’s released into the atmosphere or a pathogen- and toxin-ridden sludge that mostly winds up in incinerators or landfills. From the perspective of his microbes, Chandran says, it’s actually “enriched water,” a mélange of carbon, nitrogen, and phosphorous compounds that the microbes are happily turning into biofuels, bioplastics, fertilizers, and a host of other useful products.

Modern wastewater treatment plants represent the first great triumph of microbial-community engineering. In aeration tanks (Lower Right), air bubbles up through the brown, organic-rich water. This gives microbes the oxygen they need to digest the dissolved solids into “activated sludge,” which falls to the bottom. The water is then sent to clarification tanks (Blue Circles), where any remaining solids fall out. Image credit: Shutterstock/chekart.
The chemical pathways that his microbes use to accomplish that feat are reminiscent of the industrial fermentation processes used for millennia to make wine, yogurt, sauerkraut, and other foodstuffs. The difference is that Chandran’s colonies aren’t monocultures. They are rich microbial ecosystems comprising a diverse array of bacteria, archaea, and protozoa taken from soil, ditches, and just about any other ecological niche that researchers can find—including, yes, sewage plants. That diversity, in turn, allows these communities to accomplish feats of chemical processing that no one organism can hope to do in isolation. “In theory at least,” says Chandran, “microbes harbor infinite potential.”

And these days, he adds, that potential is being turned into practice as he and other researchers around the world learn to steer their colonies in useful directions. Granted, the actual deployment of these microbial approaches face the same real-world barriers that slow down any new technology, including high initial investment and years of planning.

But the deployment is moving forward even so, with just about every microbial systems lab forging partnerships to get the technology into working treatment plants. After all, says environmental engineer Bruce Rittmann, who has studied microbial communities at Arizona State University in Tempe since the 1980s, these systems have certain advantages that no plant manager can ignore: “Microbes work in an ambient, natural environment, with no need for super-high temperatures or other strange, risky conditions.” They can churn out marketable products that help defray the costs. And best of all, he says, “they work pretty cheap.”

### A Great Triumph

Ironically, current-generation sewage treatment plants actually represent the first great triumph of microbial systems—although the discovery was pretty much an accident. Back in Edwardian-era England, Rittmann explains, when industrial development and high-density cities had turned the rivers into stinking public health threats, sanitation engineers had few options beyond putting the polluted water into tanks to let the heavy solids settle out, then releasing the still-filthy liquid that remained back into the environment.

But in 1913, two engineers in Manchester decided to experiment with pumping air into the tanks (1). “They really didn’t know why this was a good idea,” says Rittmann, but it worked amazingly well: After a few hours or days the water had clarified as if by magic, and the solids had condensed into a mass of fibers and flakes dubbed “activated sludge.” By the 1920s, this process was being adopted by sewage treatment plants everywhere, and it is still the most widely used biological wastewater treatment in the world.

In retrospect, says Rittmann, it’s obvious what was happening: The microbial ecosystem living in the sewage got a jolt of oxygen and started metabolizing like mad. And then, after the microbes had digested all they could and had grown into a dense mat, they fell to the bottom as sludge and left the clean water behind.

But that picture didn’t really become clear until in the 1980s, when Rittmann and others started applying the fast-evolving techniques of molecular genomics (2). “The first great tool we had was looking at the ribosomal RNA,” he says: “We had an immediate ability to identify organisms by where they fit in the tree of life.”

From this, Rittmann and his fellow researchers learned that most of the real work in these microbial communities is done by the bacteria, along with various species of archaea that sometimes take over in anaerobic conditions. By the 1990s and 2000s, advances in genomics had revealed the true complexity of these microbial communities, which can easily comprise 2,000 species or more, and allowed researchers to monitor how these ecosystems were changing their chemical activity in response to their environment.

These developments, in turn, helped researchers tailor their microbial communities to carry out specific functions—a process that basically amounts to designing an environment that rewards the desired behavior before seeding it with a bit of microbe-rich soil or water. The thousands of species already present in that ecosystem will then proceed to rebalance their populations in the new environment until the best organisms for the task become dominant.

### Sewage Rethink

With these tools in hand, microbial community researchers have devoted much of their effort on a fundamental rethink of the classic activated-sludge approach to sewage.
One drawback of this method is that aeration is expensive. It consumes 60 to 80% of the energy in a wastewater treatment plant. That figure is even higher if you strip out not just the organic carbon but also nitrogen- and phosphorus-bearing compounds. The latter two can trigger algae blooms and oxygen-deprived dead zones if they’re released into enclosed bodies of water, as they often are. There are aerobic microbes in the activated sludge that can deal with nitrogen, says Chandran, who spent the early 2000s as a consultant helping New York City and other regional governments tackle the dead zone problem in Long Island Sound. But these organisms grow slowly, he says, which translates into bigger tanks and “a 40 to 100% increase of the aeration requirements.”

Phosphorus is even more problematic. The standard treatment is to add a solution containing calcium, aluminum, or iron ions that will bind the phosphorus and drag it to the bottom of the tank. But aside from having to buy the solution, says Mark van Loosdrecht, an environmental biotechnologist at the Delft University of Technology in The Netherlands, “you produce a lot of extra waste sludge, so the cost is relatively high and is less sustainable.”

Most of these problems go back to the standard approach’s near-exclusive reliance on aerobic microbes—the ones that respond so well to that energy-intensive air supply. So the general strategy of the microbial-community researchers is to do as much sewage treatment as possible anaerobically.

Central to this approach is a class of nitrogen-digesting bacteria discovered at a Dutch wastewater treatment plant in the 1990s (3–5). Known as the anaerobic ammonium oxidation (anammox) bacteria, they comprise a group of perhaps 16 species that do exactly what their name implies: They transform the ammonium ion (NH₄⁺) found in human waste and overfertilized farm runoff into harmless nitrogen gas (N₂), with minimal need for oxygen. Although these bacteria still need some aeration—the anammox reaction requires nitrite (NO₂⁻) produced by the aforementioned aerobic nitrogen microbes—they need much less of it, which can greatly reduce the cost.

In the late 1990s, van Loosdrecht’s group discovered an elegant way to exploit that fact (6, 7). They found that by subjecting the microbes in sewage plants to conditions that rewarded growth that was slow, instead of as fast as possible, they could induce the organisms to form hard, dense granules that were much easier to separate from the clean water than amorphous sludge had been. Better still, the microbes in the granules spontaneously organized themselves into concentric shells, with an aerobic zone on the outside surrounding an anaerobic zone on the inside. This meant that the granules could function as mini-factories in which aerobic and anaerobic microbes work together without needing specialized tanks and plumbing. This same layered structure could also accommodate Accumulibacter: an organism that will extract copious amounts of phosphate from the water when it cycles back and forth between aerobic and anaerobic conditions and then store the chemical in a polymerized form that’s easily harvested (8).

Taken together, says van Loosdrecht, these properties allow for wastewater treatment plants that are a quarter the size of the conventional variety and that achieve a savings of 20 to 30% in both energy use and total costs. In September 2011, after undergoing more than a decade of laboratory and pilot-plant development, the granulation technology (now with the trade name Nereda) saw its first full-scale deployment in the Dutch town of Epe. The Epe plant worked well with both municipal and industrial effluent, and by the latter half of the 2010s it had inspired dozens more Nereda projects worldwide. The current count is 67, says van Loosdrecht. And, allowing for the 5- to 10-year planning time typical of these projects, he is hoping for rapid additional growth in both Asia and North America.

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—Per Halkjær Nielsen

Meanwhile, Per Halkjær Nielsen and his team at Aalborg University in Denmark threw a wildcard into the game in 2015, when they identified a second new group of nitrogen-cycling microbes (9, 10). Known as the complete ammonia oxidation (comammox) bacteria, these organisms also do what their name says: They can oxidize ammonia all by themselves—no oxygen required. “In my world it was really a huge discovery,” says Nielsen. The comammox microbes still need a lot more lab work before they’re understood well enough for practical use, he says. But like anammox, these new bacteria have turned out to be ubiquitous in nature. “They completely rewired the way we thought about the nitrogen cycle,” he says.

From Removal to Recovery

Treating sewage is only the beginning. In the past five or 10 years, microbial ecologists have also focused on ways to convert so-called waste streams back into resources that could potentially earn the treatment plants a profit. As Nielsen puts it, “we want all those plants to be energy producing, we want them to be greenhouse-gas negative, we want them to follow a sustainable development path.”

Chandran, for example, has developed a way to take methane—a potent greenhouse gas that’s generated by certain anaerobic bacteria—and convert it into methanol: a liquid that a treatment plant can use either as a fuel or as part of a standard process to remove nitrates from the water. The trick, says Chandran, is to coax the plant’s aerobic nitrogen-cycling bacteria to carry out the methane-to-methanol conversion as a side-reaction (11).
Another popular option: generating a class of polymers known as polyhydroxyalkanoates (PHAs) by feeding the sewage to bacteria. “For the bacteria it’s like a fat reserve,” says van Loosdrecht. “But the polymer, if you extract it, has almost the same characteristics as polyethylene.” A key difference is that PHA, unlike its more familiar counterpart, is biodegradable. Small amounts of PHA bioplastic are already on the market. But van Loosdrecht is hoping to make treatment plants into a major source of the stuff: Having devised a microbial system to make PHA out of sewage (12), he is currently working with a plant in The Netherlands on a pilot demonstration.

The Delft group is also trying to develop a market for a gel-like material extracted from the Nereda granules. “It’s the extracellular polymer that bacteria use to glue themselves together,” explains van Loosdrecht. Introduced under the trade name Kaumera in 2019, the polymer can be made into composite materials that are flame-retardant and water-resistant. So far, it’s found a few niche applications, he says, notably as a biodegradable replacement for the oil-based polymers used to bind fertilizer pellets and to coat seeds. But experiments are underway to combine Kaumera with another copious sewage byproduct, the cellulose from toilet paper, to form a strong, lightweight construction material. There is a demonstration site in The Netherlands producing about 400 tons of Kaumera per year, says van Loosdrecht. Ultimately, he would like to “convert all the organic molecules in the wastewater into either PHA or into Kaumera, depending on how we steer the process.”

Scaling Down
For Chandran, such feats are part of a larger aim—microbial systems that can help sanitation-have-nots around the globe. “My thinking over the past decade or so has been transformed by these questions,” he says.

In practice, this often means deploying the microbial systems in smaller-scale, decentralized facilities instead of thinking only in terms of large, centralized treatment plants. To help these local installations off-set their costs, Chandran has been designing them to generate high-value outputs tailored for local needs.

This strategy was on display between 2011 and 2014, when the Bill & Melinda Gates Foundation funded Chandran to work with local collaborators on a series of demonstration projects in Ghana (13). In rural areas, the team re-engineered toilets to provide not just sanitation but also fertilizer for local fields. And in Kumasi, Ghana’s second-largest city, Chandran and his colleagues devised a system to convert fecal sludge into biodiesel and methanol that could be used as fuels—while keeping sludge out of the local waterways.

Ghana didn’t have the funding to continue the project after 2014, says Chandran. But he is applying the lessons learned there to his current work with Catherine Coleman Flowers, an activist in Alabama’s Black Belt (14). The region’s name refers both to its demography—majority African American—and to the dark clay soil that is great for cotton but awful for drainage. Only the most expensive septic tanks can be made to work there, which is bad news for a population that is both poor and mostly rural; many residents are forced to rely on an open pipe that takes the waste straight from the toilet to a nearby ditch or stream. Chandran is devising microbial alternatives to tackle these problems, working under an umbrella organization that he and Flowers launched at Columbia late last year: the Wastewater Innovation and Environmental Justice Lab.

The problems, though, extend far beyond Alabama. Nearly a quarter of the US population relies on septic tanks or other on-site systems that are sometimes poorly maintained and end up leeching disease-causing pathogens and nitrates into the surrounding soil and groundwater. Worse, these issues are increasingly exacerbated by a combination of climate change-induced flooding, poverty, and the general lack of investment in infrastructure.

So before he rushes in with an approach that may or may not work, says Chandran, “it’s important to figure out what is needed where.” In Alabama, he says, the appropriate output might be fertilizer for local crops. But in the arid American Southwest, the primary need might be clean drinking water.

Only when this analysis is complete will Chandran and his team start to design microbial systems that can be tailored for each site, using a mix of aerobic and anaerobic processes as needed—and making sure that the result is affordable and usable by the people it’s supposed to benefit. Scaling these approaches will also be key. What happens to the microbial communities, for example, when they start getting fed intermittently as opposed to constantly as in the case of a wastewater treatment plant?

There’s a long road ahead. But if researchers can scale these systems, and if the development and operating costs can be offset by the resources recovered, Chandran, for one, sees a “game-changing approach” in how communities deal with sewage.