COMMENT

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A treatment plant in Chongqing, China, which processes 40,000 cubic metres of wastewater per day.

Reuse water pollutants

Extracting carbon, nitrogen and phosphorus from wastewater could generate resources and save energy, say **Wen-Wei Li**, **Han-Qing Yu** and **Bruce E. Rittmann**.

Treating domestic and industrial wastewater so that it can be reused for drinking, irrigation and manufacturing is costly. The treatment of used household water from cooking, washing, cleaning and sanitation alone accounts for 3% of global electricity consumption and 5% of global non-carbon dioxide greenhouse-gas emissions (mainly methane). Industrial wastewater is more expensive to clean. Those proportions will rise in the next decade as the world's population grows and stricter water-quality standards are enforced by developing countries[1–3].

The costs could be more than recouped if valuable chemicals — including useful forms of carbon, nitrogen and phosphorus — were captured from wastewater. Water-treatment plants that harness methane could produce electricity rather than consume it[4], for instance. Scaled up, emerging technologies could efficiently and cheaply recover phosphate and ammonium for fertilizer.

What stands in the way of creating 'wastewater-resource factories'? Uncertainty[5,6] — about which techniques are most useful and how to combine them. Here, we outline one possible strategy for domestic water (see 'Wastewater works'), illustrating how treatment plants that now cost millions of dollars a year to run could be retuned to generate more than US$1 million a year for communities. Similar schemes applied to more diverse industrial wastewater would deliver further benefits.

DOWN THE DRAIN

Domestic wastewater contains the detritus of our daily lives — faeces, fat, food scraps, detergents and pharmaceuticals. In chemical terms, 1 cubic metre of domestic wastewater contains 300–600 grams of carbon-rich organic matter (known as carbonaceous chemical oxygen demand, or COD), 40–60 grams of nitrogen (in the form of ammonium and organic compounds), 5–20 grams of phosphorus (in phosphates and organic compounds), 10–20 grams of sulfur (mainly as sulfate) and traces of heavy metal ions.

For the past century, the bulk of domestic wastewater has been treated using the aerobic 'activated-sludge process': it is whisked with air and bacteria to oxidize the pollutants. The process is simple and is effective at removing organic compounds, nitrogen and phosphorus[7]. But it has a large energy and carbon footprint. A medium-sized plant (one that processes 100,000 cubic metres of water per day) consumes as much electricity as a Chinese town of 5,000 people (around 0.6 kilowatt-hours per cubic metre of wastewater) and emits as much CO_2 as 6,000 cars per day.

The energy embodied in the wastewater's organic matter is squandered. Also discarded are forms of nitrogen and phosphorus that would be valuable for making fertilizers. Precipitated by adding calcium, iron or aluminum salts, 90% of the phosphorus ends up buried in landfill because the precipitates cannot be taken up by plants and are often contaminated with toxic metals[8,9]. Likewise, more than 80% of the nitrogen is lost through conversion to nitrogen gas by microbes. The process also produces a lot of 'wet sludge' (5–10 kilograms ▶

per cubic metre of treated water). The drying and disposal (on land or in landfill) or incineration of this accounts for 30–50% of a treatment facility's overall costs.

Some wastewater plants digest the sludge anaerobically. Here, microorganisms in the absence of oxygen break down complex organic matter into simpler organic molecules[9], which are then converted into methane. By combusting the methane to produce electricity and heat[4], anaerobic digestion can offset 20–30% of the energy and greenhouse-gas costs of the activated-sludge process. But digestion is slow, taking 10–20 days.

PROMISING SYSTEMS

Applying anaerobic practices directly to domestic wastewater could reverse those costs entirely and generate an excess of energy, but it is not currently possible at ambient temperatures and with low concentrations of organics[9]. That could change with two new technologies being trialled — if they can be scaled up[4].

The first technology is the anaerobic membrane bioreactor (AnMBR). It uses a porous membrane to retain and concentrate solids (including particulate organic matter and the slow-growing microbes that produce methane gas) and more than 90% of the dissolved organic matter in wastewater[4]. By prolonging the materials' degradation time, it allows 25–100% more methane to be produced per cubic metre of treated water. More than 90% of the dissolved methane (at concentrations of 10–20 milligrams per litre) can be extracted with gas or vacuum techniques, using relatively little energy (less than 0.05 kilowatt-hours per cubic metre; kWh m^{-3}).

Several pilot AnMBRs have been successfully used for domestic wastewater treatment; a facility that can process 12 cubic metres per day at the Bucheon wastewater-treatment plant in South Korea has run for more than 2 years. The biggest challenge in scaling up this technology is preventing the membrane from becoming clogged, or 'fouled'. Using gas bubbles or fluidized granular activated carbon to scour the membrane surface clean requires a further 0.2–0.6 kWh m^{-3} of energy, comparable to that used in the activated-sludge process.

A second option involves microbial electrochemical cells (MXCs) that either generate electrical power directly, in the mode of microbial fuel cells, or produce energy-rich chemicals such as hydrogen gas in microbial electrolysis cells[10]. MXCs take advantage of the ability of some bacteria that — as they metabolize organic matter — transfer electrons through their cell membranes to receptors outside. If passed to the anode of a fuel cell, the electrons can deliver a current.

The products of MXCs — electricity or hydrogen gas — are more valuable and readily used than methane. But the reactions involved are slow (taking several days), notably the initial break-up of particulates, which account for half of the organic matter (COD) in domestic wastewater. A promising possibility is integrating MXCs with an AnMBR to speed up the conversion of organic matter while producing methane and electricity or hydrogen[10].

But current MXCs perform poorly on large scales. Enlarging or stacking multiple cells increases their resistance and lowers the efficiency at which energy may be recovered. Several pilot, cubic-metre-scale facilities for domestic wastewater treatment have been reported, including: one using 120-litre microbial-electrolysis-cell cassettes, installed in Howdon, UK, that recovers less than half of the electrical energy input as hydrogen gas; and a 250-litre microbial-fuel-cell unit installed in Harbin, China, that converts only 7% of the embodied energy in organic substances to electricity.

NUTRIENT RECOVERY

What of nitrogen and phosphorus? Anaerobic treatment releases them into the effluent as ammonium and phosphate ions. The effluent can be used to irrigate nearby fields. But more valuable are nitrogen and phosphorus in forms that can be stored and transported. One option is recovering both as struvite, a slow-release fertilizer that is precipitated by adding magnesium and lime. This is commercially viable at the high phosphate and ammonium concentrations (hundreds of milligrams per litre) found in sludge or livestock wastewater, but it is ineffective for domestic wastewater[8].

Two emerging technologies — ion exchange and electrodialysis — capture and concentrate phosphorus and nitrogen enough to be recovered from effluent as struvite[8]. In the first, phosphate ions are swapped with anions (such as carbonate) or ammonium ions swapped with cations (such as sodium ions) and adsorbed by materials such as iron-based hydroxides, zeolites and polymers. In the second, an electric field and membrane separate phosphorus and nitrogen ions from others on the basis of charge and size.

Both technologies are still being debugged on small scales. Problems include incomplete recovery of ions from the exchanger; the exchanger or membrane becoming blocked by organic matter; salts contaminating the concentrate; and cost. For example, membranes currently cost hundreds of dollars per square metre. And electrodialytic extraction (at a recovery rate of 90%) of phosphorus and nitrogen consumes roughly 0.23 kWh m^{-3} and 0.14 kWh m^{-3}, respectively — around two-thirds of the energy consumed in the activated-sludge process[8]. Use of MXCs may partly offset that energy input by generating electricity, but microorganisms and biomolecules aggravate membrane fouling[10].

"Nitrogen recovery from wastewater in particular would have a global impact."

Nitrogen recovery from wastewater in particular would have a global impact. In the lab, extraction of nitrogen has received less attention than has phosphorus extraction, because atmospheric nitrogen gas can be easily reduced to synthesize nitrogen fertilizer. But the process involved — the nitrogen-fixing Haber–Bosch process — is energy intensive: it accounts for a few per cent of the world's annual energy use. Substituting just 5% of the existing nitrogen-fertilizer production would save more than 50 terawatt-hours of energy, or 1.5% of China's annual electricity consumption.

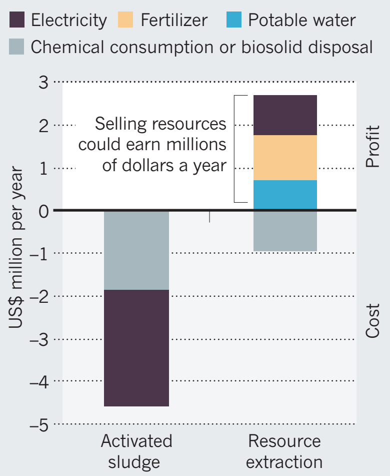
Biosolids — biomass from microbial growth and undigested faeces, fibres and other solids from the wastewater — are other by-products of anaerobic digestion that contain nitrogen and phosphorus. If they are stabilized (to avoid generating methane gas or odours) and detoxified (no pathogens or hazardous chemicals) during anaerobic treatment, they can be applied directly to the soil[5]. The United States spreads 55% of its treated biosolids onto the land, but this practice is under public and regulatory pressure because the waste is difficult to stabilize and detoxify completely, and heavy metals accumulate.

Heat treatment makes biosolids easier and safer to use. It kills pathogens, improves nutrient retention and lessens heavy-metal release. Heat from combusted methane can be used to lower energy needs[4], but the safety of biosolid products still needs to be improved and evaluated at larger scales.

The final product — water — has huge

POLLUTANTS TO PROFITS

Capturing energy, nitrogen, phosphorus and water can turn wastewater treatment from a major cost into a source of profit.



Estimates for a plant processing 100,000 m^3 of wastewater per day.

SOURCE: W.-W.L., H.-Q.Y., B.E.R.

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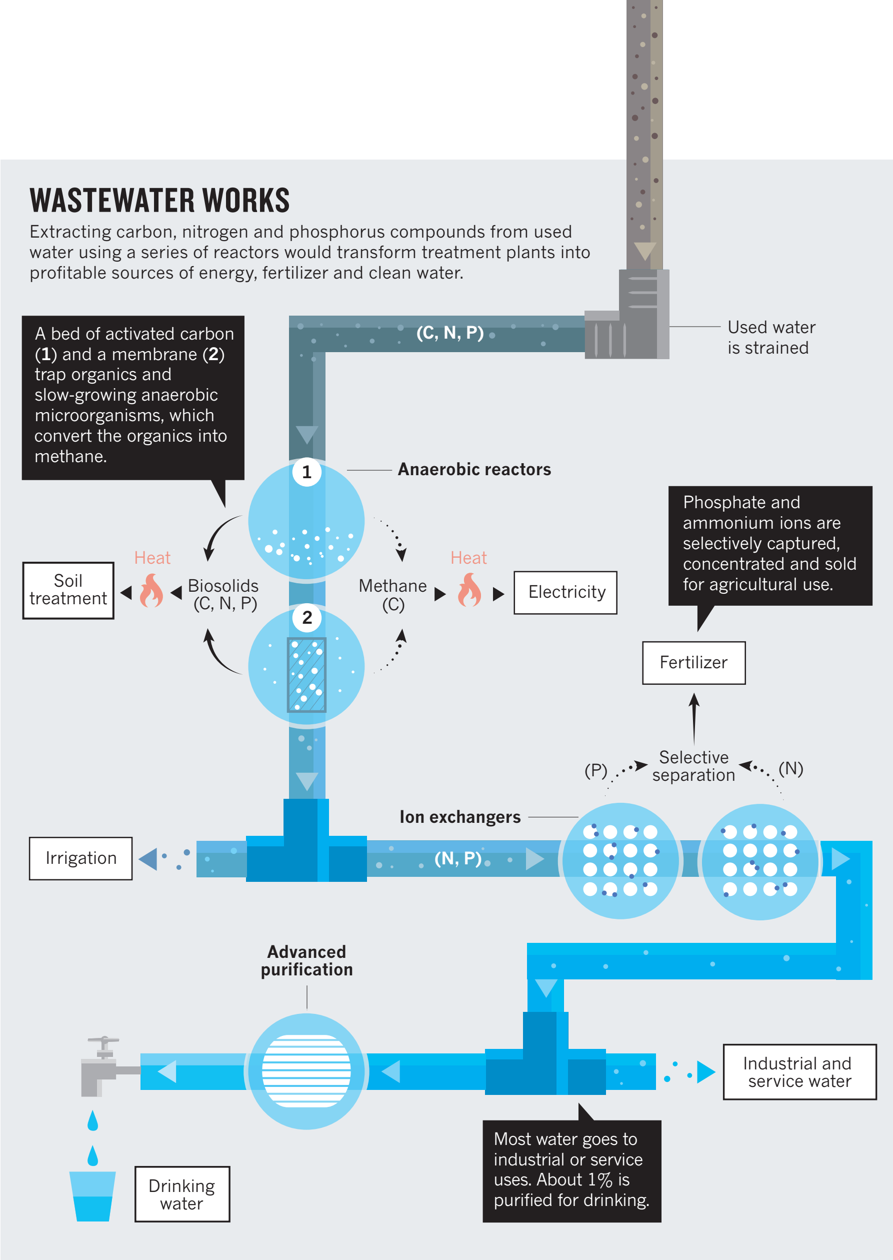

WASTEWATER WORKS

Extracting carbon, nitrogen and phosphorus compounds from used water using a series of reactors would transform treatment plants into profitable sources of energy, fertilizer and clean water.

economic value: the global average price for potable water is $2 per cubic metre. Each type of use requires water of a different quality — from the cleanest for drinking to lower-quality water for cooling or industry uses. The treatment technology needed varies accordingly. In China, only 15% of treated water is reused and up to 98% of potable water goes to municipal and industrial sectors that could make do with lower-quality water. A 'fit-for-purpose' treatment and reuse strategy is needed.

ECONOMIC BENEFITS

We estimate that a domestic wastewater-resource factory serving a city of about half a million people in China would treat around 100,000 cubic metres of domestic wastewater per day. We calculate that each day it could produce around 17,000 kWh of electrical energy, recover 1 tonne of phosphorus and 5 tonnes of nitrogen, and reclaim 1,000 cubic metres of potable water. By contrast, an activated-sludge plant (with anaerobic digestion) of the same size would consume 50,000 kWh of electrical energy and recover no phosphorus or nitrogen. A resource factory would thus save 67,000 kWh per day (and that is without considering the energy saved in fertilizer production). This is equivalent to 1.5% of the city's daily electricity consumption.

We estimate that such a factory could yield a profit of $1.8 million per year (excluding construction costs), compared with a cost of $4.6 million per year for an activated-sludge-treatment plant (see 'Pollutants to profits'). That assumes the sale of only the 1% of water made drinkable; profits could be ten times higher if non-potable water were sold.

The economic boon could be higher still for industrial wastewaters in the agricultural, food and petrochemical sectors[1]. For example, AnMBRs can remove up to 98% of the organic matter (around 18 kilograms per cubic metre) from petrochemical effluent, producing 100 times more methane than is achievable with domestic wastewater. Livestock wastewater is rich in organic molecules and phosphorus, making it an important potential source of energy and fertilizer[8].

Government support will be crucial to developing wastewater-resource factories and promoting a sustainable water-resource market. For the next decade, extracting resources from wastewater will remain expensive relative to fossil-fuel energy and current processing methods. Why? Because environmental costs are not yet factored into pricing and emerging recovery technologies have not yet benefited from economies of scale. Priorities will change as energy, resource and global-warming stresses intensify.

What next? Governments must establish regulatory frameworks that include the costs of waste disposal and greenhouse-gas emissions. They must invest in demonstrations at scale of the pre-commercial or early-adopter technologies; initially subsidize the sales of recovered products; and promote the benefits of the recycled-resource concept.

Governments and enterprises in the sector should provide targeted research funds as well as land and infrastructure. To ensure that the products are suitable, technological development must involve input from regulators, managers of wastewater facilities, engineers, researchers and the public.

National initiatives are needed that suit local environmental, economic and social conditions. Industrialized countries should integrate the emerging processes when they replace ageing treatment facilities. And emerging economies such as China and India should incorporate them as they expand their water-treatment capacities. ■

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