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# Pathways to advanced resource recovery from sewage

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 Check for updates

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The ongoing paradigm shift in sewage management from pollution control to resource recovery is an integral part of a circular economy. Efforts have traditionally concentrated on the recovery of organic carbon as bioenergy, and nitrogen and phosphorus as nutrients. In the past decade, technologies have been developed to recover high-value commodities. Simultaneously, innovative processes have been proposed to produce chemical agents that can be immediately reused in the sewage system to facilitate sewage management. This Review evaluates these latest developments and the underpinning scientific discoveries, identifies the key challenges, and outlines a roadmap towards greener and more sustainable sewage management.

For over a century, sewage treatment has primarily focused on pollution control, with organic matter oxidized to carbon dioxide (CO<sub>2</sub>), reactive nitrogen (N) converted to dinitrogen gas and less- and non-biodegradable materials condensed into a solid stream for disposal as a waste. These technologies have served well to protect human health and our aquatic environments, but they perform poorly in resource efficiency.

The imperative to transition to a circular and low-carbon economy is resulting in a paradigm shift in the perception of sewage, from a mere waste to a stream encompassing valuable resources<sup>1</sup>. Sewage treatment plants (STPs) are being recognized as trinity production

facilities, coined as Nutrient + Energy + Water (NEW) factories, which are expected to recover nutrients, energy and recycled water efficiently<sup>2</sup>. As an example, by 2013, the Sheboygan STP in Wisconsin, USA, was able to offset 90–115% and 85–90% of its in-plant electricity and heat consumption, respectively, by utilizing power and heat generated with biogas produced from anaerobic digestion (AD) of excess sludge and imported food waste<sup>2</sup>. Similarly, the Strass STP in Austria achieved energy self-sufficiency rates of 108% via AD of the organic carbon upfront separated from sewage and 200% via co-digestion of sewage sludge and imported kitchen waste<sup>3</sup>. These examples have successfully showcased the potential for energy recovery from sewage.

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Substantial progress has also been made in nutrient recovery, although full-scale cases remain sparse. Water reuse and water recycling have been even more successful than energy and nutrient recovery, with numerous installations worldwide at STPs, industrial wastewater treatment plants, and commercial and residential sites<sup>4</sup>.

In parallel to the recovery of water, energy and nutrients, considerable efforts have been devoted in recent years to the direct recovery of raw materials from sewage and valuable chemicals produced in sewage treatment. These products have much higher value than the NEW products and represent important opportunities. Some of these materials have also been proposed for use in the treatment process itself, enabling a direct reuse and circular economy within the water utilities themselves.

In this paper, we review and discuss these latest advances and identify pathways to advanced resource recovery from sewage. Water reuse has been extensively reviewed and discussed elsewhere<sup>4</sup> and is not covered in this paper. Similarly, the energy and nutrients in animal, food and food-processing wastes are not covered, although they often have mass flows higher than in sewage<sup>1</sup>.

## State-of-the-art technologies for harvesting resources from sewage

### Bioenergy and heat energy recovery

Sewage is a reservoir of chemical energy, primarily encapsulated in organic compounds. This latent energy can be recovered via AD, a process that converts organics to biogas in the absence of oxygen. The resulting biogas is predominantly composed of methane and CO<sub>2</sub>. Biogas can be converted to heat and electricity by combined heat and power generators ((1) in Fig. 1). On a global scale, AD has emerged as a robust technology installed at many medium to large STPs. In Europe alone, 11% (~2,600) of STPs have adopted AD as of 2021<sup>5</sup>, collectively producing around 3.5 TWh of electricity per year. In comparison, 7.5% (~1,200) of STPs in the United States have adopted AD<sup>6</sup>. The uptake of AD in China is currently less than 5% (~60), largely owing to the lower sewage organic content in most parts of China<sup>7</sup>.

From secondary sludge, AD typically yields 110–145 l of methane (at 25 °C, 1 atm) per kilogram of volatile solids added<sup>8</sup>, about two to three times lower than the yield from primary sludge. To compensate for the relatively low methane yield of secondary sludge, many pretreatment technologies have explored options to enhance methane production. Thermal hydrolysis pretreatment, which enhances biogas production by 20–50%, is the most prevalent, with nearly 100 full-scale facilities operational. These methods also substantially increase the dewaterability of the AD sludge and hence dramatically reduce sludge disposal costs. Other widely studied and pilot-tested pretreatment methods include mechanical (for example, ultrasound) and chemical (for example, free nitrous acid (FNA) and alkali) treatment, which increases biogas production and volatile solid destruction by 10–40%<sup>9</sup>.

Anaerobic treatment of mainstream sewage has been adopted in developing countries such as Brazil, Mexico and India, where cost reduction (due to lower sludge yield and lower energy consumption) is the key driver<sup>10</sup>. The produced methane, including the dissolved methane in the effluent, is not always collected, although collection is essential to avoid substantial emissions of methane as a potent greenhouse gas. Mainstream anaerobic sewage treatment has the potential to double methane production compared with sludge<sup>11</sup>. Its adoption is mainly impeded by high retrofitting costs and operational challenges, including inadequate N removal<sup>12</sup>, which may be solved by autotrophic nitrogen removal (for example, partial nitrification and anammox)<sup>13</sup>.

The value of biogas when converted to power and/or heat is relatively low. Biogas can be upgraded to higher-value biomethane (a gas akin to natural gas), volatile fatty acids (VFAs) or hydrogen gas (H<sub>2</sub>) (through methane reforming)<sup>14</sup>. CO<sub>2</sub> in biogas can also be converted to biomass or VFAs by photosynthetic microorganisms or acetogenic bacteria<sup>15</sup>, but research is still in its infancy.

Sewage contains considerable heat energy from bathing, laundry and cooking, as well as the relatively warm micro-climate in houses. Much of the heat is conserved in sewers and STPs. There have been many commercial applications for thermal energy recovery directly from sewage<sup>16</sup>, which has often been problematic due to operational difficulties (fouling and corrosion). Also, a decrease in the sewage temperature usually results in undesired decreases in biological activities at the STP. In general, the temperature of treated effluent, albeit lower than the influent temperature, is still well above that of the receiving water body, making it a suitable place for heat recovery ((2) in Fig. 1). Technologically, water source heat pumps can be an effective means to recover heat from the STP effluent for heating or cooling. For example, the heat recovered can be used to dry excess sludge to reduce the volume of disposed sludge. With a coefficient of performance of 3–5, the net electrical equivalent of water source heat pumps can be as high as 1.77 kWh m<sup>-3</sup> for heating, six to eight times larger than the chemical energy recoverable via biogas<sup>17</sup>.

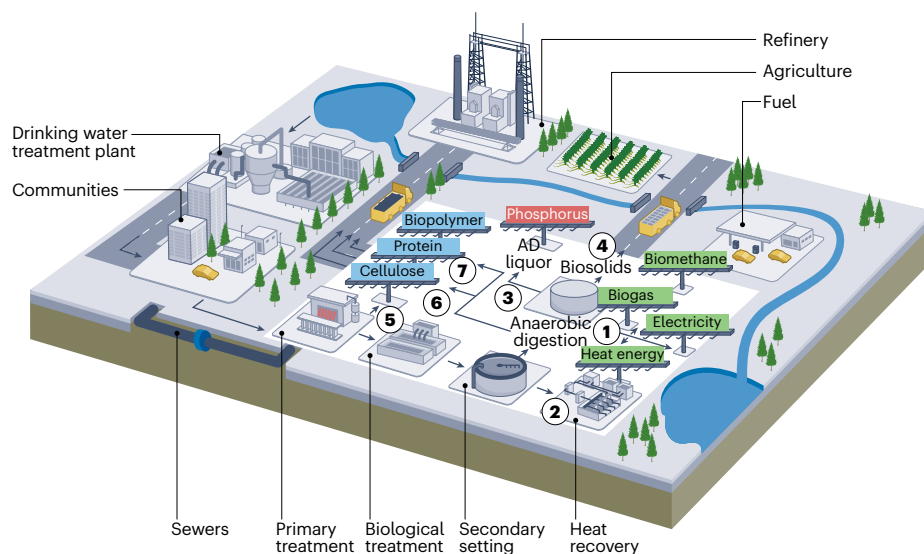
### Nutrient recovery

Sewage contains notable amounts of N and phosphorus (P). However, their recovery directly from the sewage is economically challenging due to their low concentrations at 40–50 mg N l<sup>-1</sup> and 5–10 mg P l<sup>-1</sup>. In practice, research has focused more on their recovery in the sludge line, where N and P are at much higher concentrations.

Phosphorus as a non-renewable resource critically supports global food production, necessitating its recovery<sup>18</sup>. About 25% of the P applied as fertilizer in agriculture finds its way to sewage (calculated on the basis of data reported in the literature<sup>19</sup>). The demand for phosphate rocks could be reduced by 15–20% if all the P in sewage were recovered and recycled<sup>20</sup>. Selective ion exchange, such as the hybrid anion exchange process, has been proposed to recover P directly from sewage, but the afterlife of the hybrid anion exchange resin and its disposal remain a challenge<sup>21</sup>. Through chemical precipitation or biological uptake, the current wastewater treatment technologies remove P in sewage to negligible levels, with almost all P in sewage enmeshed in the sludge, as biomass, intracellular polyphosphate and/or chemical precipitates. The final fate of P depends on how the sludge is treated and used or disposed of.

The most widespread P recovery approach consists of phosphate precipitation in the form of struvite (MgNH<sub>4</sub>PO<sub>4</sub>, or MAP) in the anaerobic sludge digestion liquor, which contains phosphate at concentrations of 50–150 mg P l<sup>-1</sup> (ref. 22). The process involves the addition of Mg(OH)<sub>2</sub> to elevate the pH and Mg<sup>2+</sup> levels, leading to favourable conditions for MAP formation and achieving P recovery efficiencies of over 90% ((3) in Fig. 1). The recovery of P as MAP also results in the recovery of a small amount of N. As an alternative to MAP, calcium-phosphate compounds (CaP) such as hydroxyapatite ((Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>(OH)) or tricalcium phosphate (Ca<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>) could also be used for P recovery from the anaerobic sludge digestion liquor, typically achievable via the addition of lime to elevate pH and Ca<sup>2+</sup> levels. Both MAP and CaP are well recognized as slow-release fertilizers. However, the marketability and profitability of these processes are hampered by the products not consistently meeting the market requirements of well-defined and uniform products in large quantities. It is worth noting that the original reason for MAP or CaP precipitation at STPs was to prevent blockage of the downstream pipes and facilities due to uncontrolled precipitation, which is still a strong driver even at present.

With the above pathways, the recovered P represents only 10–25% of the P mass load to the STPs<sup>23</sup>, as anaerobic sludge digestion does not fully liberate P embedded in sludge. If the biosolids are recycled to agricultural land, the remaining P is recycled via this pathway. However, the direct agricultural reuse of sewage-derived biosolids is not always possible due to legal restrictions addressing real or perceived risks associated with pathogenic organisms, heavy metal contents and organic pollutants<sup>24</sup>. In some countries, sewage-derived biosolids



Sewage resources	Highlights	Challenges and opportunities
<b>1. Biogas</b>	<ul style="list-style-type: none"> <li>Bioenergy recovery via AD</li> <li>Mature technology and wide implementation in many medium to large STPs</li> </ul>	<ul style="list-style-type: none"> <li>Low financial return due to high CO<sub>2</sub> content</li> <li>CH<sub>4</sub> leak in storage tanks after digesters</li> <li>Limited application scope outside the plant</li> </ul>
<b>2. Heat</b>	<ul style="list-style-type: none"> <li>Heat recovery in biogas combustion or from treated sewage (effluent)</li> <li>High recoverable heat energy: six to eight times larger than chemical energy</li> </ul>	<ul style="list-style-type: none"> <li>Limited application scope, as reclaimed heat energy is typically used within the plant or by the local community due to grid constraints</li> </ul>
<b>3. Phosphorus</b>	<ul style="list-style-type: none"> <li>Recovery from AD liquor via chemical precipitation of dissolved P</li> <li>Wide applicability in STPs equipped with AD and dewatering processes</li> </ul>	<ul style="list-style-type: none"> <li>Low recovery efficiency representing only 10–25% of the P mass load to the STPs</li> <li>Limited market price, relatively low quantities and varied quality upon decentralized production</li> </ul>
<b>4. Biosolid fertilizer</b>	<ul style="list-style-type: none"> <li>Biosolids as a nutrient-containing, slow-release fertilizer for agricultural reuse</li> <li>High recovery efficiency with more than 80% of the P mass load to the STPs retained in biosolid fertilizer</li> </ul>	<ul style="list-style-type: none"> <li>Perceived risks tied to pathogens, heavy metals, and organic and emerging pollutants in biosolids</li> </ul>
<b>5. Cellulose</b>	<ul style="list-style-type: none"> <li>Recovery of cellulose from used toilet paper via physical separation using a rotating belt filter</li> <li>Reuse for biofuel production and paper manufacturing, among other opportunities</li> </ul>	<ul style="list-style-type: none"> <li>Advancements in sewage treatment technologies enable more efficient recovery of cellulose</li> <li>Market increase is expected from US\$17.6 billion in 2022 to US\$42.24 billion by 2032</li> </ul>
<b>6. Biopolymers</b>	<ul style="list-style-type: none"> <li>Extraction of PHA and EPS from sludge offering environmental benefits over traditional plastics</li> <li>PHA use in packaging and consumer goods as eco-friendly alternatives to petroleum-based plastics</li> <li>EPS as potential bioflocculant, raw material for biocomposites and flame-retarding materials</li> </ul>	<ul style="list-style-type: none"> <li>Higher production costs than conventional plastics</li> <li>Increasing demand for global sustainability; for example, PHA market size is expected to increase from US\$93 million in 2022 to US\$195 million by 2028</li> </ul>
<b>7. Protein</b>	<ul style="list-style-type: none"> <li>Protein recovery from sludge through microbial fermentation with competitive price over traditional protein sources</li> <li>Protein as feedstock for animal feed, aquaculture and potentially human consumption as a protein supplement or meat substitute</li> </ul>	<ul style="list-style-type: none"> <li>Increased commercial viability by advances in fermentation and purification processes</li> <li>Market increases due to environmental concerns and regulations—for example, for SCP, from US\$13.1 billion in 2022 to US\$75.9 billion by 2032</li> </ul>

**Fig. 1 | Technologies and commodities.** State-of-the-art technologies for harvesting important sewage resources and some marketable high-value commodities in an STP.

are incinerated. Phosphorus is left in the ash in this case, which could be safely stored for future mining. Following mono-incineration of sludge, P mining from the ash (containing 50–100 g P per kg total solids) is established using wet-chemical leaching or thermochemical approaches, potentially enabling a high recovery rate of 60–90%, relative to the influent sewage P load<sup>25</sup>.

Iron salts (Fe<sup>2+</sup> or Fe<sup>3+</sup>) are often used in sewage systems for sulfide control (in sewers), chemical phosphate removal or sludge settleability

improvement. In these cases, vivianite (Fe<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>) is often the dominant form of iron phosphate in the sludge<sup>26</sup>, even when iron salt is initially added to the sewer network<sup>27</sup>. Vivianite is a paramagnetic material that can be directly recovered with a magnetic separation process<sup>28</sup>. This allows 60–80% of the influent phosphate to be recovered. The recovered vivianite can be used in agriculture as an iron fertilizer<sup>29</sup>. There is also the option to separate iron and P as K<sub>3</sub>PO<sub>4</sub> (or H<sub>3</sub>PO<sub>4</sub>) and FeCl<sub>2</sub>. Iron can be reused within the STP, while P can be used as a fertilizer ((4) in

Fig. 1). The European Union is preparing legislation to demand at least 50% recovery of influent P; recovery as vivianite is currently the only technology that can reach this goal other than biosolid land application and sludge incineration. Notably, another iron-phosphate solid,  $\text{FePO}_4$ , can be formed in sludge. Like  $\text{AlPO}_4$ , it is generally not available for plants and is difficult to recover. Furthermore, the natural occurrence of non-phosphate P species, which are in diverse (and sometimes even unknown) forms with different properties<sup>30</sup>, poses additional challenges to recovery.

Unlike P, which is a finite resource (and hence its recovery or storage for future recovery is compulsory), reactive N ( $\text{NH}_3$ ) can be produced using the Haber–Bosh process, with the expenditure of methane at 25 GJ per tonne N in modern plants. This means that a comprehensive economic analysis based on energy balance and life-cycle assessment is needed to determine the overall costs and benefits of N recovery.

Ammonia stripping is currently the most mature technology for N recovery. It is generally considered economically sensible only if the wastewater stream contains ammonium at a minimum concentration of  $1 \text{ g N l}^{-1}$ , achievable in digestion liquor of well-operated anaerobic sludge digesters. To recover N from wastewater with  $1 \text{ g N l}^{-1}$ , the energy consumption is approximately 23.6 kWh per kg N (11.6 kWh per kg N for a  $10^\circ \text{C}$  temperature elevation plus 10 kWh per kg N to produce NaOH for pH elevation to above the pKa value of ammonium plus 2 kWh per kg N for sulfuric acid production, required for capturing  $\text{NH}_3$  in ammonium salts (database: ecoinvent 3.8, OpenLCA)). This is roughly equivalent to the sum of the energy required for synthesizing ammonium using the Haber–Bosh process (12.5 kWh per kg N) and that required for N removal via nitrification and denitrification (12 kWh per kg N)<sup>31</sup>. Nitrogen removal via partial nitritation and anammox has a lower energy consumption of 4.2 kWh per kg N<sup>31</sup>, which means an even higher wastewater N concentration is needed for N recovery to be sensible.

Other N recovery technologies including membrane-based separation, ion-exchange adsorption, and electrochemical and bio-electrochemical systems are also being researched<sup>32</sup>. They are subject to the same economic constraints outlined above. All these technologies are at early stages, with electrodialysis through ion-exchange membranes being the only one demonstrated at pilot scale with real AD effluent. Nitrogen recovery was achieved with an energy consumption of 4.3–6.5 kWh per kg N<sup>33,34</sup>, but a rapid loss of current density was observed due to membrane scaling and clogging, a major challenge shared by all systems using membranes. A key unsolved challenge for adsorption-based processes is the regeneration of the adsorbents, critical for their economic viability.

A promising strategy is to combine the above technologies to recover N from streams with relatively low concentrations. Such a hybrid approach could address the limitations of individual technologies, delivering a cost-effective and environmentally favourable process<sup>35</sup>.

Approximately 80% of the N, 40% of the P and 90% of the potassium (K) in sewage originate from urine, which represents <1% of the sewage flow<sup>36</sup>. There is therefore a compelling case for urine separation and nutrient recovery directly from urine. The key issue is the high costs associated with the construction and maintenance of highly decentralized systems. However, there is a good potential to install such systems in commercial buildings, where urinals collect large amounts of urine without faecal contamination. The direct use of urine as a liquid fertilizer was common in arid areas for centuries. The World Health Organization guidelines require urine wastewater to be stored for at least six months to inactivate pathogens<sup>37</sup> or to be put through a partial nitrification process<sup>38</sup>; both require costly large-volume storage facilities. To reduce the volume, urine dewatering by evaporation, distillation, membrane filtration or freezing has been studied, but the high capital or operational costs remain an issue<sup>39</sup>. Nutrient extraction from source-separated urine offers an alternative. For instance, P and K can

be recovered as K-struvite ( $\text{MgKPO}_4 \cdot 7\text{H}_2\text{O}$ )<sup>40</sup>, an analogue of struvite, or as a concentrated nutrient stream with the potential of recovering pure  $\text{NH}_4\text{HCO}_3$  crystals<sup>41</sup>. These technologies are feasible in large-scale centralized urine treatment plants where urine is transported through pipe and truck transportation.

## Emerging technologies for transforming wastes into high-value commodities

Technologies have emerged in more recent years to derive products with much higher values than the common NEW products. Some are readily present in sewage, while others are formed during sewage treatment. Three specific examples, recovering cellulose, biopolymers and proteins, are reviewed here for their strong commercial potentials ((5), (6) and (7) in Fig. 1).

### Cellulose recovery from sewage

Cellulose is a primary component of toilet paper and a slowly biodegradable organic substance. Toilet paper is physically disintegrated in the sewer network and reaches STPs in the form of linear cellulose. Estimated to be over  $100 \text{ mg l}^{-1}$ , cellulose accounts for approximately 35% of the total suspended solids (SS) in sewage<sup>42</sup>. It can be recovered via physical separation using, for example, a rotating belt filter. A commercial technology, CellCap, has been installed at a few full-scale installations to harvest cellulose from sewage. The recovered cellulose has been used as a raw material for biocomposites and construction.

The upfront recovery of cellulose in sewage substantially reduces sludge production in STPs, as cellulose is hardly biodegradable and accumulates in sludge. A 50% recovery from sewage containing cellulose at  $100 \text{ mg SS l}^{-1}$  is estimated to reduce the mixed liquor SS concentration by up to  $1.5 \text{ g SS l}^{-1}$ , assuming a hydraulic retention time of 12 hours and a sludge age of 15 days ( $0.1 \text{ g SS l}^{-1} \times 50\% \times 15 \text{ d} / 0.5 \text{ d} = 1.5 \text{ g SS l}^{-1}$ ). This substantially reduces solid loading rates to secondary clarifiers and excess sludge production.

### Biopolymer recovery from sludge

Organic carbon removal in sewage treatment generates polymeric byproducts that accumulate in sludge. These include intracellular carbon storage polymers (polyhydroxyalkanoates or PHAs) and extracellular polymeric substances (EPS); both are of particular interest and have been recognized as high-value materials, around 10–20 times the value of biogas that can be produced from the same amount of organic carbon.

PHA is a biodegradable polymer that can replace polyethylene or polypropylene in the plastics market. Bacteria in activated sludge produce and consume PHAs in response to the availability of organic carbon<sup>43</sup>. PHA is produced and stored by bacteria when ample readily biodegradable carbon substrates are available, and it is consumed as a carbon and energy source when external carbon substrates deplete. The PHA content in sewage sludge can reach roughly 50% of the volatile SS, and it can reach 80–90% in sludge from treating organics-rich industrial wastewater<sup>44,45</sup>. Many technologies are available to extract PHA from activated sludge, among which solvent extraction is the most commonly used<sup>46</sup>. Extraction refers to separating PHA from non-PHA molecules (or residual biomass). The PHA accumulation and extraction processes have been demonstrated in numerous laboratory studies and implemented at a pilot plant scale (25 kg per day) in the Netherlands. PHA potentially replaces non-biodegradable plastics but lacks a strong economic driver at present. New applications are needed to develop a full value chain, for which adhesives might be an interesting option.

Bacteria produce EPS to form flocs, granules or biofilms. These polymers represent a considerable fraction of the sludge. While the specific EPS compounds are not well characterized<sup>47</sup>, EPS in floccular sludge and in granular sludge generally resembles polyelectrolytes and gelling polymers, respectively<sup>48</sup>. Gelling polymers are particularly in high demand since it is difficult to produce these polymers

from oil-based chemicals. The gelling polymers in granular sludge can be extracted with the same technology used for alginate extraction from seaweed<sup>48</sup>. There are currently demonstration facilities in the Netherlands with a production capacity of a few hundred tonnes per year. Following extraction, the remaining sludge residue can still be used for biogas production. The recovered EPS have found their first application in agriculture for fertilizer pelletization or seed coating, replacing non-biodegradable polymers<sup>49</sup>. The good water-binding capacity of EPS gels also makes them a good soil amendment in irrigated agricultural land<sup>50</sup>. Furthermore, granular EPS have very good heat and flame resistance, with properties suitable for application in, for example, the aviation industry as fire-retardant materials or the construction industry as good binders in the production of composite materials<sup>51</sup>. These high-value applications make strong business cases for EPS recovery from granular sludge.

### Protein recovery from sewage

Sewage-based protein concepts typically rely on open symbiotic cultures of bacteria (and/or eukaryotic microalgae) that are dried<sup>52</sup>. Even though proteins constitute a major mass fraction, other compounds including carbohydrates, lipids, nucleic acids, vitamins, trace elements and antioxidants are also present. Such single-cell protein (SCP) provides an alternative protein source in the agri-food chain but has a much lower environmental footprint than other protein sources such as soybeans<sup>53</sup>.

SCP production directly in the sewage treatment line, termed 'mainstream SCP', enables the largest production potential (in tonnes of SCP per year). However, its use may, for safety reasons, be restricted to soil applications. Aerobically, high-rate activated sludge processes can redirect higher portions of organics and N to SCP, but purple phototrophic bacteria, which assimilate all organics with light energy, give the highest production potential<sup>54</sup>. Microalgae provide an autotrophic (or mixotrophic) phototrophic alternative, often in conjunction with aerobic heterotrophs in so-called microalgae–bacteria flocs, typically considered for nutrient recovery after part of the organics is removed<sup>55</sup>.

Risks can be more easily managed in the sludge line, increasing the value of 'sidestream SCP'. Anaerobic conversion is typically used to convert the organic carbon in sludge to VFAs or methane. Biogas is free of pathogens and non-volatile contaminants (for example, heavy metals) through the gas phase transition and has been tested to produce SCP by methane-oxidizing bacteria<sup>56</sup>. VFAs can be extracted with membranes, which avoids the transfer of faecal pathogens, and used as carbon sources by purple phototrophic bacteria or aerobes<sup>57</sup>. As discussed above, nutrients recovered from the sludge line, for instance with ammonia stripping/scrubbing and/or struvite precipitation, can be used to fertilize SCP production<sup>58,59</sup>.

### Converting wastes into chemical agents for circular use in sewage management

A challenge in sewage resource recovery is the absence of a well-developed marketable value chain for sewage-derived commodities. Water utilities traditionally operate without selling products in a commercial market, while materials and chemical industries are not used to buy resources from distributed production sites under governmental oversight. The lack of such an efficient and reliable value chain poses a substantial limitation to the scalable recovery of high-value commodities from sewage. Considering this, innovative processes have been developed to recover chemical agents that can be immediately reused in the sewage system to facilitate sewage management, including the enhanced recovery of other resources. As these products do not enter the market as commodities, the quality requirements are much more relaxed, incurring much lower production costs. Compared with the recovery and utilization of resources for other markets, the utilization of resources within a sewage system tends to be more feasible, accessible and widely applicable.

### Carbonaceous chemicals

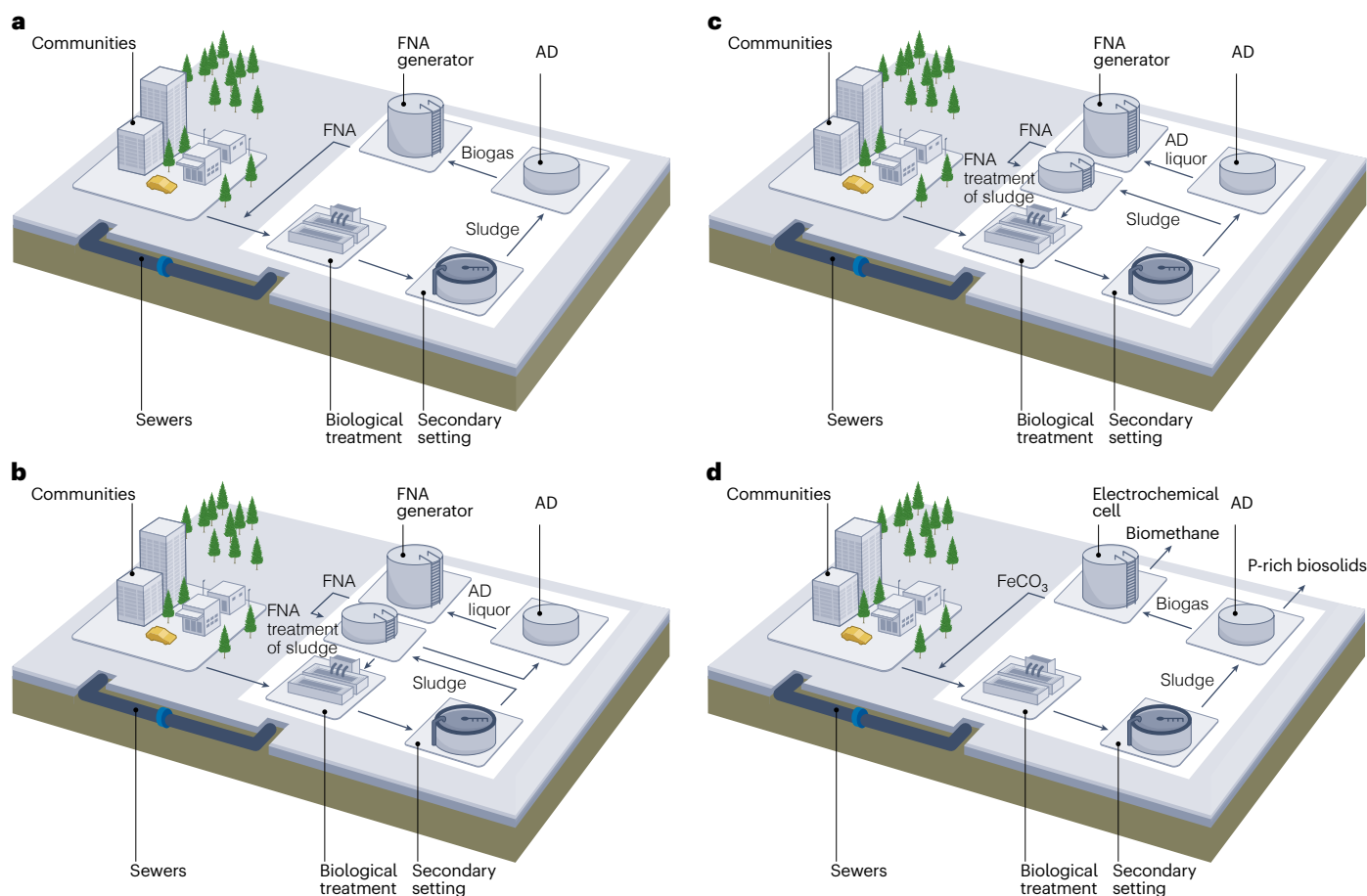
As a classic example, VFAs derived from sludge fermentation have proved exceptionally adept at facilitating cost-effective denitrification and biological P removal<sup>60</sup>, due to their high biodegradability<sup>61</sup>. VFAs produced from sludge fermentation are not marketable products due to low concentrations and contamination. However, when replacing externally imported organic carbon (for example, methanol or acetate) to support N and/or P removal, their value is elevated to that of the marketed VFAs, with the additional benefit of saving transport and dosing costs. Indeed, VFA production has become a standard feature in many STPs, which incorporates either a sidestream or a mainstream sludge fermentation unit<sup>62,63</sup>.

Maximum bioenergy recovery requires upfront carbon separation for biogas production, which creates difficulties for biological N removal. Although the mainstream anammox process can theoretically remove N without the need for organic carbon, the effluent often contains a relatively high level of nitrate produced by anammox bacteria or unwanted nitrite-oxidizing bacteria<sup>64</sup>. Over the past decade, innovative processes have been developed to use methane in biogas as the organic carbon source for high-level N removal from sewage, in conjunction with anammox bacteria. These technologies have been demonstrated in biofilms<sup>65–68</sup>, granules<sup>69</sup> and membrane bioreactors. These forms of growth were needed to retain the slow-growing microorganisms performing nitrite/nitrate-dependent anaerobic methane oxidation (n-DAMO)<sup>70,71</sup>. A mere 5% of the biogas produced is sufficient to facilitate complete nitrate removal in a partial nitrification–anammox process<sup>72</sup>. This is because n-DAMO organisms have low yields, ensuring highly effective use of the electrons in methane for nitrate/nitrite reduction. This also substantially reduces excess sludge production, compared with heterotrophic bacteria growing on traditional carbon sources. More recently, the n-DAMO and anammox consortia have been exploited to remove N from the effluent of anaerobically treated mainstream sewage, where dissolved methane in the anaerobic effluent, accounting for up to 40% of the total methane produced, was used for nitrate/nitrite reduction<sup>73</sup>. This process also substantially reduces the stripping of dissolved methane into the atmosphere as a potent greenhouse gas.

### Nitrogenous chemicals

FNA at parts-per-million levels is biocidal to a broad range of microorganisms, causing cell death and lysis<sup>74</sup>. Several technologies have been developed that use FNA to improve sewage management. These include the dosage of FNA to sewers to control anaerobic sewer biofilms, thus alleviating sewer odour and corrosion (Fig. 2a), as demonstrated in full-scale applications<sup>75</sup>; and the use of FNA to pretreat secondary sludge prior to AD (Fig. 2b)<sup>76,77</sup>. In the latter case, both laboratory- and pilot-scale experiments have demonstrated 30–40% increases in biogas production and volatile solid destruction due to improved sludge biodegradability. The capacity of a digester could be doubled due to the much-improved sludge hydrolysis rate<sup>76</sup> and much-reduced sludge viscosity<sup>77</sup>. The response of functional microorganisms to the biocidal effects of FNA varies. Specifically, ammonia-oxidizing bacteria are more resistant to FNA than nitrite-oxidizing bacteria<sup>78</sup>. This inherent discrepancy has been strategically harnessed to selectively eliminate nitrite-oxidizing bacteria from activated sludge, thereby fostering innovative, energy-efficient nitrogen removal (Fig. 2c), as demonstrated in both laboratory-scale<sup>79</sup> and pilot-scale studies<sup>80,81</sup>.

Instead of importing chemicals (nitrite and acid) for the above applications, processes have been proposed to produce FNA on-site at STPs<sup>82</sup>. An anaerobic sludge digester liquor contains ammonium at 0.5–1.5 g N l<sup>-1</sup>, which can be converted to nitrite by ammonia-oxidizing bacteria. Due to the consumption of alkalinity in ammonia oxidation, the processed digestion liquor contains a high level of nitrite and a negligible level of alkalinity. The FNA production unit can be easily integrated with the FNA treatment unit, leading to an innovative process



**Fig. 2 | Transforming waste into nitrogenous and iron chemical agents for circular use in sewage management. a**, Use of FNA for odour and corrosion control. **b**, Use of FNA in the pretreatment of sludge prior to AD. **c**, Use of FNA in sidestream sludge treatment for short-cut nitrogen removal in the mainstream. **d**, Production and reuse of ferrous carbonate ( $\text{FeCO}_3$ ) in an urban sewage system.

that simultaneously achieves high-level N removal and enhanced bio-energy recovery. This stands as an exemplary illustration of the reuse of a 'recovered' chemical in sewage management.

The reuse of in situ produced FNA has recently been extended to aerobic digestion of waste activated sludge<sup>83</sup> and anaerobically digested sludge<sup>84</sup>. Both types of sludge contain a high level of organic N, which is released as ammonia, the oxidation of which produces nitrite and acid. Operational strategies have been developed that lead to the persistent accumulation of nitrite, which, coupled with a low pH (<5), gives rise to FNA levels up to  $10 \text{ mg N l}^{-1}$  (ref. 83). Such conditions substantially improve sludge degradation and pathogen destruction<sup>84</sup>. FNA production and accumulation have also been achieved in a mainstream sewage treatment reactor via the use of a novel acid-tolerant ammonia-oxidizing bacterium, '*Candidatus Nitrosoglobus*'<sup>85</sup>. FNA at  $2 \text{ mg N l}^{-1}$  could be maintained at a nitrite concentration around  $40 \text{ mg N l}^{-1}$  and a low pH of 4.65, tolerable by '*Candidatus Nitrosoglobus*'.

Analogous to FNA, free ammonia at high concentrations (for example,  $>200 \text{ mg N l}^{-1}$ ) is also biocidal to microorganisms. It can be produced at an STP by alkalinizing the anaerobic sludge digestion liquor. Its in situ application for sewage and sludge treatment has also been researched<sup>86</sup>, in some cases in conjunction with FNA<sup>87</sup>.

### Iron chemicals

Iron chemicals in various forms (for example,  $\text{FeCl}_2$  and  $\text{FeCl}_3$ ) have been widely used in sewage management<sup>88</sup>. They are dosed at multiple points in a sewerage system, including sewers and anaerobic

sludge digesters for hydrogen sulfide control<sup>89</sup> as well as STPs at various locations for phosphate removal and sludge settleability improvement<sup>90</sup>. Recent research has shown that iron salts dosed to sewers, removing sulfide, could be regenerated in the aeration basin and 'reused' for precipitation of phosphate and improved sludge settleability. The same iron is further reused in an anaerobic sludge digester to remove sulfide and improve sludge dewaterability. These multiple regenerations and reuses are caused by the changed redox conditions in different process units and occur naturally so long as iron salts are added early in the sewerage system (that is, sewers).

Ferric salts are often used as coagulants in drinking water treatment, generating waste iron sludge. The iron-containing drinking water sludge, when dosed to sewers, achieves all the benefits of imported iron salts, including the flowing-on effects<sup>91</sup>. No recovery of iron or preprocessing of the sludge is needed prior to sewer dosage.

One issue of  $\text{FeCl}_2$  or  $\text{FeCl}_3$  use in sewerage systems is the consumption of alkalinity, leading to undesirable pH decreases. Ferrous carbonate ( $\text{FeCO}_3$ ) is a potentially more desirable iron salt, as it adds alkalinity to sewage. An electrochemical process was developed recently that produces  $\text{FeCO}_3$  through the precipitation of electrochemically produced  $\text{Fe}^{2+}$  (from Fe) with  $\text{CO}_3^{2-}$  formed by capturing  $\text{CO}_2$  in biogas (Fig. 2d)<sup>92</sup>. The produced  $\text{FeCO}_3$  has the beneficial effects of the commonly used iron salts but elevates rather than decreases sewage pH<sup>92</sup>. By capturing  $\text{CO}_2$ , the process upgrades biogas to more valuable biomethane. The proposed process also enables water utilities to establish a self-reliant and more secure supply of iron salts.

## Other emerging options and opportunities

With existing and emerging technologies extracting energy, nutrients and valuable chemicals from sewage, current STPs still discharge a substantial amount of organics as residual solids, typically representing 25–35% of that in the feed<sup>93</sup>. This fraction is poorly biodegradable or non-biodegradable with chemical and microbial contaminations and is thus often landfilled or incinerated. One potential approach to recycle this last part of the organics is their conversion to syngas via gasification, which is much less susceptible to contamination, and the subsequent conversion of the gaseous constituents (CO, CO<sub>2</sub> and H<sub>2</sub>) to valuable products via microbial gas fermentation. This pathway should be used as the last resort, as there is considerable energy loss in gasification, and the reassembling of C<sub>1</sub> compounds and H<sub>2</sub> to complex chemicals is not energy efficient. However, syngas contains energy, and its conversion to chemicals is substantially more energy efficient than the use of CO<sub>2</sub> (for example, in flue gases) alone. Microbial gas fermentation is preferable to chemical catalytic approaches due to its lower capital and operational costs; it is thus more suitable for small gas sources such as that produced at an STP. In the field of industrial biotechnology, numerous studies in either pure or mixed cultures have demonstrated the feasibility and practicality of microbial conversion of syngas to liquid chemicals<sup>94,95</sup> and microbial proteins as animal feeds or feed supplements<sup>96,97</sup>.

For N recovery, a novel and attractive approach (alternative to its recovery as fertilizer or protein) is the cracking of the stripped ammonia into H<sub>2</sub> as an energy source<sup>98</sup>. This may become an important option in the future, considering that the value chain for recovered nutrients for agriculture is increasingly hampered by regulatory requirements and by the major technological developments in plant production requiring standardized fertilizers.

Most resource recovery processes applied or proposed today are add-on features to existing treatment processes. They are often driven by internal economic factors. Opportunities for more effective resource recovery will probably be created through re-imagining the overall process design and considering resource recovery as an integral design goal. This requires integrating new knowledge generated from multidisciplinary research, including the exploration, discovery and application of novel microorganisms and innovative materials.

It should be underscored that, to a large extent, the successful implementation of sewage resource recovery hinges on consumer acceptance and regulatory support. While technological advancements have paved many ways for resource extraction, the ultimate success of these initiatives lies in their acceptance by both end users and regulatory bodies as well as in good value chains that integrate the sewage treatment sector with the chemical and materials producing industries.

## References

- Li, W.-W., Yu, H.-Q. & Rittmann, B. E. Chemistry: reuse water pollutants. *Nature* **528**, 29–31 (2015).
  - Shen, Y., Linville, J. L., Urgun-Demirtas, M., Mintz, M. M. & Snyder, S. W. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: challenges and opportunities towards energy-neutral WWTPs. *Renew. Sustain. Energy Rev.* **50**, 346–362 (2015).
  - Lackey, K. & Fillmore, L. *Energy Management for Water Utilities in Latin America and the Caribbean: Exploring Energy Efficiency and Energy Recovery Potential in Wastewater Treatment Plants* (World Bank Group, 2017).
  - Salgot, M. & Folch, M. Wastewater treatment and water reuse. *Curr. Opin. Environ. Sci. Health* **2**, 64–74 (2018).
  - Task 37: A Perspective on the State of the Biogas Industry from Selected Member Countries, 2021* (IEA Bioenergy, 2023).
  - Renewable Natural Gas Production* (US Department of Energy, 2023); [https://afdc.energy.gov/fuels/natural\\_gas\\_renewable.html](https://afdc.energy.gov/fuels/natural_gas_renewable.html)
  - Cao, Y., Van Loosdrecht, M. & Daigger, G. T. The bottlenecks and causes, and potential solutions for municipal sewage treatment in China. *Water Pract. Technol.* **15**, 160–169 (2020).
  - Bougrier, C., Delgenes, J.-P. & Carrère, H. Combination of thermal treatments and anaerobic digestion to reduce sewage sludge quantity and improve biogas yield. *Process Saf. Environ. Prot.* **84**, 280–284 (2006).
  - Zhen, G., Lu, X., Kato, H., Zhao, Y. & Li, Y.-Y. Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: current advances, full-scale application and future perspectives. *Renew. Sustain. Energy Rev.* **69**, 559–577 (2017).
  - Van Haandel, A., Kato, M. T., Cavalcanti, P. F. & Florencio, L. Anaerobic reactor design concepts for the treatment of domestic wastewater. *Rev. Environ. Sci. Bio/Technol.* **5**, 21–38 (2006).
  - McCarty, P. L., Bae, J. & Kim, J. Domestic wastewater treatment as a net energy producer—can this be achieved? *Environ. Sci. Technol.* **45**, 7100–7106 (2011).
- Wastewater treatment can become a net generator of energy rather than a large energy consumer.**
- Chernicharo, C. Post-treatment options for the anaerobic treatment of domestic wastewater. *Rev. Environ. Sci. Bio/Technol.* **5**, 73–92 (2006).
  - Wang, Z., Zheng, M., Duan, H., Yuan, Z. & Hu, S. A 20-year journey of partial nitrification and anammox (PN/A): from sidestream toward mainstream. *Environ. Sci. Technol.* **56**, 7522–7531 (2022).
- N removal via anammox reduces energy consumption and increases bioenergy recovery.**
- Angelidaki, I. et al. Biogas upgrading and utilization: current status and perspectives. *Biotechnol. Adv.* **36**, 452–466 (2018).
  - Zuo, Z. et al. Biological bromate reduction coupled with in situ gas fermentation in H<sub>2</sub>/CO<sub>2</sub>-based membrane biofilm reactor. *Water Res.* **254**, 121402 (2024).
  - Cipolla, S. S. & Maglionico, M. Heat recovery from urban wastewater: analysis of the variability of flow rate and temperature in the sewer of Bologna, Italy. *Energy Procedia* **45**, 288–297 (2014).
  - Hao, X., Li, J., van Loosdrecht, M. C., Jiang, H. & Liu, R. Energy recovery from wastewater: heat over organics. *Water Res.* **161**, 74–77 (2019).
- Thermal energy recovery and utilization in wastewater.**
- Mayer, B. K. et al. Total value of phosphorus recovery. *Environ. Sci. Technol.* **50**, 6606–6620 (2016).
  - Brunner, P. H. Substance flow analysis as a decision support tool for phosphorus management. *J. Ind. Ecol.* **14**, 870–873 (2010).
  - Yuan, Z., Pratt, S. & Batstone, D. J. Phosphorus recovery from wastewater through microbial processes. *Curr. Opin. Biotechnol.* **23**, 878–883 (2012).
  - Guida, S., Rubertelli, G., Jefferson, B. & Soares, A. Demonstration of ion exchange technology for phosphorus removal and recovery from municipal wastewater. *Chem. Eng. J.* **420**, 129913 (2021).
  - Latif, M. A., Mehta, C. M. & Batstone, D. J. Enhancing soluble phosphate concentration in sludge liquor by pressurised anaerobic digestion. *Water Res.* **145**, 660–666 (2018).
  - Egle, L., Rechberger, H. & Zessner, M. Overview and description of technologies for recovering phosphorus from municipal wastewater. *Resour. Conserv. Recycl.* **105**, 325–346 (2015).
  - Wang, Z. et al. Post-treatment options for anaerobically digested sludge: current status and future prospect. *Water Res.* **205**, 117665 (2021).
  - Egle, L., Rechberger, H., Krampe, J. & Zessner, M. Phosphorus recovery from municipal wastewater: an integrated comparative technological, environmental and economic assessment of P recovery technologies. *Sci. Total Environ.* **571**, 522–542 (2016).

26. Prot, T. et al. Full-scale increased iron dosage to stimulate the formation of vivianite and its recovery from digested sewage sludge. *Water Res.* **182**, 115911 (2020).
27. Salehin, S. et al. Recovery of in-sewer dosed iron from digested sludge at downstream treatment plants and its reuse potential. *Water Res.* **174**, 115627 (2020).
28. Prot, T. et al. Magnetic separation and characterization of vivianite from digested sewage sludge. *Sep. Purif. Technol.* **224**, 564–579 (2019).
29. Fodoué, Y., Nguetnkam, J., Tchameni, R., Basga, S. & Penaye, J. Assessment of the fertilizing effect of vivianite on the growth and yield of the bean ‘Phaseolus vulgaris’ on oxisoils from Ngaoundere (central north Cameroon). *Int. Res. J. Earth Sci.* **3**, 18–26 (2015).
30. Jia, Y. et al. Phosphorus in water: a review on the speciation analysis and species specific removal strategies. *Crit. Rev. Environ. Sci. Technol.* **53**, 435–456 (2023).
31. Lackner, S. et al. Full-scale partial nitrification/anammox experiences—an application survey. *Water Res.* **55**, 292–303 (2014).
32. Ye, Y. et al. A critical review on ammonium recovery from wastewater for sustainable wastewater management. *Bioresour. Technol.* **268**, 749–758 (2018).
33. Ferrari, F. et al. Ammonia recovery from anaerobic digester centrate using onsite pilot scale bipolar membrane electro dialysis coupled to membrane stripping. *Water Res.* **218**, 118504 (2022).
34. Kuntke, P. et al. Energy-efficient ammonia recovery in an up-scaled hydrogen gas recycling electrochemical system. *ACS Sustain. Chem. Eng.* **6**, 7638–7644 (2018).
35. Guida, S. et al. Resilience and life cycle assessment of ion exchange process for ammonium removal from municipal wastewater. *Sci. Total Environ.* **783**, 146834 (2021).
36. Larsen, T. A. & Gujer, W. Separate management of anthropogenic nutrient solutions (human urine). *Water Sci. Technol.* **34**, 87–94 (1996).
37. Stenström, T. A. *Guidelines on the Safe Use of Urine and Faeces in Ecological Sanitation Systems* (EcoSanRes Programme, 2004).
38. Aurin—‘The World’s First Urine Fertilizer with Complete Approval’ (Switzerland) (SuSanA, 2019); <https://forum.susana.org/175-urine-reuse-or-infiltration/23643-aurin-the-world-s-first-urine-fertilizer-with-complete-approval-switzerland>
39. Patel, A., Mungray, A. A. & Mungray, A. K. Technologies for the recovery of nutrients, water and energy from human urine: a review. *Chemosphere* **259**, 127372 (2020).
40. Xu, K. et al. The precipitation of magnesium potassium phosphate hexahydrate for P and K recovery from synthetic urine. *Water Res.* **80**, 71–79 (2015).
41. Ledezma, P., Jermakka, J., Keller, J. & Freguia, S. Recovering nitrogen as a solid without chemical dosing: bio-electroconcentration for recovery of nutrients from urine. *Environ. Sci. Technol. Lett.* **4**, 119–124 (2017).
42. Ruiken, C., Breuer, G., Klaversma, E., Santiago, T. & Van Loosdrecht, M. Sieving wastewater—cellulose recovery, economic and energy evaluation. *Water Res.* **47**, 43–48 (2013).
43. Morgan-Sagastume, F. et al. Production of polyhydroxyalkanoates in open, mixed cultures from a waste sludge stream containing high levels of soluble organics, nitrogen and phosphorus. *Water Res.* **44**, 5196–5211 (2010).
44. Estévez-Alonso, Á., Pei, R., van Loosdrecht, M. C., Kleerebezem, R. & Werker, A. Scaling-up microbial community-based polyhydroxyalkanoate production: status and challenges. *Bioresour. Technol.* **327**, 124790 (2021).
45. Tamis, J., Lužkov, K., Jiang, Y., van Loosdrecht, M. C. & Kleerebezem, R. Enrichment of *Plasticicumulans acidivorans* at pilot-scale for PHA production on industrial wastewater. *J. Biotechnol.* **192**, 161–169 (2014).
46. Kurian, N. S. & Das, B. Comparative analysis of various extraction processes based on economy, eco-friendly, purity and recovery of polyhydroxyalkanoate: a review. *Int. J. Biol. Macromol.* **183**, 1881–1890 (2021).
47. Seviour, T. et al. Extracellular polymeric substances of biofilms: suffering from an identity crisis. *Water Res.* **151**, 1–7 (2019).
48. Felz, S., Vermeulen, P., van Loosdrecht, M. C. & Lin, Y. M. Chemical characterization methods for the analysis of structural extracellular polymeric substances (EPS). *Water Res.* **157**, 201–208 (2019).
49. Fertahi, S., Ilsouk, M., Zeroual, Y., Oukarroum, A. & Barakat, A. Recent trends in organic coating based on biopolymers and biomass for controlled and slow release fertilizers. *J. Control. Release* **330**, 341–361 (2021).
50. Costa, O. Y., Raaijmakers, J. M. & Kuramae, E. E. Microbial extracellular polymeric substances: ecological function and impact on soil aggregation. *Front. Microbiol.* **9**, 1636 (2018).
51. Kim, N. K. et al. Flame retardant property of flax fabrics coated by extracellular polymeric substances recovered from both activated sludge and aerobic granular sludge. *Water Res.* **170**, 115344 (2020).
- Carbonated hydroxyapatite of EPS extracted from granules makes flax fabrics flame retardant.**
52. Javourez, U., Matassa, S., Vlaeminck, S. E. & Verstraete, W. Ruminations on sustainable and safe food: championing for open symbiotic cultures ensuring resource efficiency, eco-sustainability and affordability. *Microb. Biotechnol.* **17**, e14436 (2024).
53. Sakarika, M. et al. Purple non-sulphur bacteria and plant production: benefits for fertilization, stress resistance and the environment. *Microb. Biotechnol.* **13**, 1336–1365 (2020).
54. Capson-Tojo, G. et al. Purple phototrophic bacteria for resource recovery: challenges and opportunities. *Biotechnol. Adv.* **43**, 107567 (2020).
- Development of PPB for protein recovery from wastewater.**
55. Aditya, L., Mahlia, T. I., Nguyen, L. N., Vu, H. P. & Nghiem, L. D. Microalgae–bacteria consortium for wastewater treatment and biomass production. *Sci. Total Environ.* **838**, 155871 (2022).
56. Ma, Y., Liu, T., Yuan, Z. & Guo, J. Single cell protein production from methane in a gas-delivery membrane bioreactor. *Water Res.* **259**, 121820 (2024).
57. Alloul, A. et al. Capture–ferment–upgrade: a three-step approach for the valorization of sewage organics as commodities. *Environ. Sci. Technol.* **52**, 6729–6742 (2018).
58. Bertasini, D., Binati, R. L., Bolzonella, D. & Battista, F. Single Cell Proteins production from food processing effluents and digestate. *Chemosphere* **296**, 134076 (2022).
59. Muys, M. et al. Dissolution rate and growth performance reveal struvite as a sustainable nutrient source to produce a diverse set of microbial protein. *Sci. Total Environ.* **866**, 161172 (2023).
60. Wang, D. et al. Side-stream enhanced biological phosphorus removal (S2EBPR) process improves system performance—a full-scale comparative study. *Water Res.* **167**, 115109 (2019).
61. Kang, D. et al. Redirecting carbon to recover VFA to facilitate biological short-cut nitrogen removal in wastewater treatment: a critical review. *Water Res.* **238**, 120015 (2023).
62. Fan, Z., Zeng, W., Liu, H., Jia, Y. & Peng, Y. A novel partial denitrification, anammox-biological phosphorus removal, fermentation and partial nitrification (PDA-PFPN) process for real domestic wastewater and waste activated sludge treatment. *Water Res.* **217**, 118376 (2022).
63. Zhang, F. et al. An innovative process for mature landfill leachate and waste activated sludge simultaneous treatment based on partial nitrification, in situ fermentation, and anammox (PNFA). *Environ. Sci. Technol.* **56**, 1310–1320 (2021).

64. Lotti, T. et al. Pilot-scale evaluation of anammox-based mainstream nitrogen removal from municipal wastewater. *Environ. Technol.* **36**, 1167–1177 (2015).
65. Liu, T. et al. Biogas-driven complete nitrogen removal from wastewater generated in side-stream partial nitrification. *Sci. Total Environ.* **745**, 141153 (2020).
66. Fu, L. et al. Hollow fiber membrane bioreactor affects microbial community and morphology of the DAMO and Anammox co-culture system. *Bioresour. Technol.* **232**, 247–253 (2017).
67. Fan, S.-Q. et al. Nitrate/nitrite dependent anaerobic methane oxidation coupling with anammox in membrane biotrickling filter for nitrogen removal. *Environ. Res.* **193**, 110533 (2021).
68. Liu, T., Hu, S., Yuan, Z. & Guo, J. High-level nitrogen removal by simultaneous partial nitrification, anammox and nitrite/nitrate-dependent anaerobic methane oxidation. *Water Res.* **166**, 115057 (2019).
69. Fan, S.-Q. et al. Granular sludge coupling nitrate/nitrite dependent anaerobic methane oxidation with anammox: from proof-of-concept to high rate nitrogen removal. *Environ. Sci. Technol.* **54**, 297–305 (2019).
70. Ettwig, K. F. et al. Nitrite-driven anaerobic methane oxidation by oxygenic bacteria. *Nature* **464**, 543–548 (2010).
71. Haroon, M. F. et al. Anaerobic oxidation of methane coupled to nitrate reduction in a novel archaeal lineage. *Nature* **500**, 567–570 (2013).
72. Liu, T., Hu, S. & Guo, J. Enhancing mainstream nitrogen removal by employing nitrate/nitrite-dependent anaerobic methane oxidation processes. *Crit. Rev. Biotechnol.* **39**, 732–745 (2019).
73. Lu, Y. et al. Coupling partial nitrification, anammox and n-DAMO in a membrane aerated biofilm reactor for simultaneous dissolved methane and nitrogen removal. *Water Res.* **255**, 121511 (2024).
74. Wu, J. et al. Role of free nitrous acid in the pretreatment of waste activated sludge: extracellular polymeric substances disruption or cells lysis? *Chem. Eng. J.* **336**, 28–37 (2018).
75. Jiang, G. et al. Dosing free nitrous acid for sulfide control in sewers: results of field trials in Australia. *Water Res.* **47**, 4331–4339 (2013).
76. Zhang, L. et al. Increasing capacity of an anaerobic sludge digester through FNA pre-treatment of thickened waste activated sludge. *Water Res.* **149**, 406–413 (2019).
77. Meng, J. et al. Free nitrous acid pre-treatment enhances anaerobic digestion of waste activated sludge and rheological properties of digested sludge: a pilot-scale study. *Water Res.* **172**, 115515 (2020).
78. Wang, Q., Ye, L., Jiang, G., Hu, S. & Yuan, Z. Side-stream sludge treatment using free nitrous acid selectively eliminates nitrite oxidizing bacteria and achieves the nitrite pathway. *Water Res.* **55**, 245–255 (2014).
79. Wang, Z. et al. Unravelling adaptation of nitrite-oxidizing bacteria in mainstream PN/A process: mechanisms and counter-strategies. *Water Res.* **200**, 117239 (2021).
80. Zheng, M. et al. One-year stable pilot-scale operation demonstrates high flexibility of mainstream anammox application. *Water Res. X* **19**, 100166 (2023).
81. Duan, H. et al. Achieving robust mainstream nitrite shunt at pilot-scale with integrated sidestream sludge treatment and step-feed. *Water Res.* **223**, 119034 (2022).
82. Law, Y. et al. Producing free nitrous acid—a green and renewable biocidal agent—from anaerobic digester liquor. *Chem. Eng. J.* **259**, 62–69 (2015).
83. Wang, Z. et al. Acidic aerobic digestion of anaerobically-digested sludge enabled by a novel ammonia-oxidizing bacterium. *Water Res.* **194**, 116962 (2021).
84. Duan, H., Ye, L., Lu, X., Batstone, D. J. & Yuan, Z. Self-sustained nitrite accumulation at low pH greatly enhances volatile solids destruction and nitrogen removal in aerobic sludge digestion. *Environ. Sci. Technol.* **53**, 1225–1234 (2018).
85. Wang, Z. et al. Robust nitrification sustained by acid-tolerant ammonia-oxidizing bacteria. *Environ. Sci. Technol.* **55**, 2048–2056 (2021).
86. Liu, Y. et al. The roles of free ammonia (FA) in biological wastewater treatment processes: a review. *Environ. Int.* **123**, 10–19 (2019).
87. Duan, H., Ye, L., Lu, X. & Yuan, Z. Overcoming nitrite oxidizing bacteria adaptation through alternating sludge treatment with free nitrous acid and free ammonia. *Environ. Sci. Technol.* **53**, 1937–1946 (2019).
88. Salehin, S. et al. Opportunities for reducing coagulants usage in urban water management: the Oxley Creek Sewage Collection and Treatment System as an example. *Water Res.* **165**, 114996 (2019).
89. Pikaar, I. et al. Reducing sewer corrosion through integrated urban water management. *Science* **345**, 812–814 (2014).
90. Hu, Z. et al. Novel use of a ferric salt to enhance mainstream nitrogen removal from anaerobically pretreated wastewater. *Environ. Sci. Technol.* **57**, 6712–6722 (2023).
91. Rebosura, M. Jr et al. Effects of in-sewer dosing of iron-rich drinking water sludge on wastewater collection and treatment systems. *Water Res.* **171**, 115396 (2020).
92. Hu, Z. et al. Integrated urban water management by coupling iron salt production and application with biogas upgrading. *Nat. Commun.* **14**, 6405 (2023).
- Wastewater, sludge and biogas management using recycled iron and recycled CO<sub>2</sub>.**
93. Mininni, G., Laera, G., Bertanza, G., Canato, M. & Sbrilli, A. Mass and energy balances of sludge processing in reference and upgraded wastewater treatment plants. *Environ. Sci. Pollut. Res.* **22**, 7203–7215 (2015).
94. Liew, F. et al. Gas fermentation—a flexible platform for commercial scale production of low-carbon-fuels and chemicals from waste and renewable feedstocks. *Front. Microbiol.* **7**, 694 (2016).
95. Köpke, M. & Simpson, S. D. Pollution to products: recycling of ‘above ground’ carbon by gas fermentation. *Curr. Opin. Biotechnol.* **65**, 180–189 (2020).
96. Matassa, S., Verstraete, W., Pikaar, I. & Boon, N. Autotrophic nitrogen assimilation and carbon capture for microbial protein production by a novel enrichment of hydrogen-oxidizing bacteria. *Water Res.* **101**, 137–146 (2016).
97. Ritala, A., Häkkinen, S. T., Toivari, M. & Wiebe, M. G. Single cell protein—state-of-the-art, industrial landscape and patents 2001–2016. *Front. Microbiol.* **8**, 2009 (2017).
98. Spatolisano, E., Pellegrini, L. A., de Angelis, A. R., Cattaneo, S. & Roccaro, E. Ammonia as a carbon-free energy carrier: NH<sub>3</sub> cracking to H<sub>2</sub>. *Ind. Eng. Chem. Res.* **62**, 10813–10827 (2023).

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### Author contributions

M.Z. and Z.Y. led the conceptualization. M.Z. prepared the first draft of the manuscript. Z.H., T.L., M.S., E.I.P.V., Z.W., X. Hao, H.D., S.E.V., K.X., Z.Z., J.G., X. Huang, G.T.D., W.V. and M.C.M.v.L. contributed to writing according to their areas of expertise. Z.Y. led the paper revisions.

### Competing interests

The authors declare no competing interests.

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