Resource Recovery from Wastewater
What, Why, and Where?

Hao, Xiaodi; Li, Ji; Liu, Ranbin; van Loosdrecht, Mark C.M.

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Xiaodi Hao,* Ji Li, Ranbin Liu, and Mark C. M. van Loosdrecht

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Existential threats from climate change and environmental degradation, coupled with increasing awareness of the depletion of natural resources, have increased the importance of sustainable development and climate neutrality. Although they protect human health, wastewater production and treatment processes contribute to increasing "material entropy", inducing environmental deterioration. Resource recovery from wastewater, instead of destroying or removing resources, can significantly minimize entropy production.[1,2] Therefore, there is a pressing need for an improved resource recovery framework to manage and reduce the climate risks associated with wastewater treatment, which is in accordance with global climate ambitions such as the EU Green Deal and the China carbon-neutral goal.

Resource recovery from wastewater is frequently portrayed as a process that converts seemingly worthless resources into valuable products, such as organic matter, nutrients, energy, and water. In practice, a lack of clarity concerning exactly what should be appropriately recovered, where, and why persists, so it is important that the what, why, and where (W^3) of potential resources from wastewater should be better defined.

First, organics (COD) contain exergy and carbonaceous materials. Traditionally, COD is oxidized into carbon dioxide (CO_2) in biological treatment processes, with excess sludge anaerobically digested for the harvesting of biogas. However, biogas production is often viewed favorably and may even receive subsidies, but its efficiency and sustainability (entropy production!) are disputed. Furthermore, the efficiency of conversion from chemical (COD) energy into electricity and heat is <15%.[3] In fact, COD can offer an opportunity for conversion into valuable organic products, like extracellular polymeric substances (EPS), polyhydroxyalkanoates (PHA), and hydrocolloids.[4] Such an approach not only generates substantial benefits for resource recovery and sustainability but

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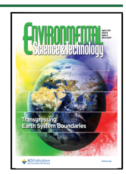

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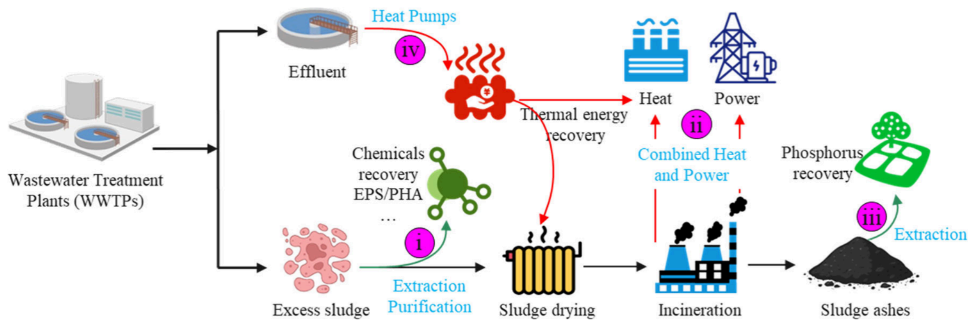

Figure 1. Steps and cruxes of the recovery of resources and energy from wastewater: (i) producing and extracting highly valuable chemicals from organics, (ii) maximizing energy recovery by direct incineration to generate power, (iii) recovering phosphorus from ash, and (iv) extracting thermal energy from the effluent.

also contributes to the replacement of oil-based chemicals in society.[2]

Second, phosphorus recovery is a critical necessity due to the imminent depletion of accessible phosphate rock reserves, a scenario anticipated within roughly 40 years. Therefore, recovering phosphorus from wastewater is more preferred than removing it. Although struvite ($MgNH_4PO_4{\cdot}6H_2O$) and vivianite [$Fe_3(PO_4)_2{\cdot}8H_2O$] can be recovered at wastewater treatment plants (WWTPs), phosphate in incinerated sludge ash is high in phosphate content (≥90% of influent P load) and technically easy to recover.[5] Along with these processes, some rare metals and elements can be additionally recovered from the ash.

With regard to nitrogen recovery, the positive environmental impacts of recovering nitrogen are only outcompeted with inaccessible resources. However, nitrogen is different from phosphorus as it is not a limiting element for society. In addition to environmental considerations, nitrogen recovery should also focus on addressing the energy deficits involved in producing ammonium from nitrogen gas and the recovery of ammonium from wastewater. The Haber–Bosch process is a well-established and cost-effective method for producing synthetic ammonia such as carbamide/urea. The recovery of nitrogen from wastewater is often more energy-intensive and logistically complex. Efficient ammonium recovery is only feasible with concentrated liquids like urine, but the implementation demands a more complicated and resource-intensive collection system.

Third, to offset the energy deficits and achieve a carbon-neutral operation of WWTPs, solar energy seems to be attractive, but the areas of WWTPs allow the production of only ~10% of the required energy. Anaerobic digestion of excess sludge has been met with skepticism in the broader context of energy recovery. Sludge drying followed by incineration has been proposed to be more efficient in the context of energy recovery.[5] The efficiency of conversion of chemical energy based on influent COD can reach 32% via incineration,[5] surpassing that of anaerobic digestion (<15%). Furthermore, decarbonized hydrogen production based on wastewater effluent has also been promoted in recent years. However, it necessitates integration with excess green (wind/solar) energy and/or off-peak fossil-based electricity. Otherwise, a situation in which the loss outweighs the gain might arise, with ~20% energy loss during energy conversion.

The thermal energy in effluent offers a significantly greater potential for recovery compared to chemical and solar energy. In essence, the recoverable amount of thermal energy is 6–8 times greater than the amount of chemical energy present in the influent COD of 400 mg/L. The calculated net recoverable electrical energy equivalent is 1.77 kWh/m^3 (ΔT = 4 °C; COP = 3.5) for heating purposes exchanged by water source heat pumps and 1.18 kWh/m^3 (ΔT = 4 °C; COP = 4.8) for cooling.[3] Thermal energy can be harnessed for district heating/cooling, agricultural greenhouses, and even drying of dewatered sludge. Therefore, it would be highly beneficial for water and energy utilities to collaborate in jointly planning the utilization of this thermal energy. Of course, it is important to emphasize that thermal energy exchange should be performed on the effluent of WWTPs rather than in sewers, as the latter would decrease the temperature in WWTPs and thereby impact the biological treatment efficiency of the plant.

A resource-based wastewater treatment within the context of the circular/blue economy is presented in Figure 1. This road map involves four critical steps: (i) producing and extracting highly valuable chemicals from organics found in wastewater and/or excess activated sludge whenever possible (examples of the chemicals being PHA and hydrocolloids), (ii) maximizing the recovery of chemical energy (COD) from excess sludge by direct incineration to generate power, rather than relying on anaerobic digestion to produce biogas, (iii) collecting and recycling phosphorus from ash produced by sludge incineration, and (iv) extracting thermal energy from the effluent for various applications, such as drying excess sludge or heating buildings or agricultural greenhouses, with the aim of indirectly offsetting electrical energy demands for wastewater treatment.

AUTHOR INFORMATION

Corresponding Author

Xiaodi Hao – *Sino-Dutch R&D Centre for Future Wastewater Treatment Technologies/Beijing Advanced Innovation Centre of Future Urban Design, Beijing University of Civil Engineering and Architecture, Beijing 100044, P. R. China;* orcid.org/0000-0001-6414-9566; Phone: +86-131 61347675; Email: haoxiaodi@bucea.edu.cn; Fax: +86-10-68322123

Authors

Ji Li – *Sino-Dutch R&D Centre for Future Wastewater Treatment Technologies/Beijing Advanced Innovation Centre of Future Urban Design, Beijing University of Civil Engineering and Architecture, Beijing 100044, P. R. China; Department of Biotechnology, Delft University of Technology, 2629 HZ Delft, The Netherlands;* orcid.org/0000-0001-6477-2892

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Ranbin Liu – *Sino-Dutch R&D Centre for Future Wastewater Treatment Technologies/Beijing Advanced Innovation Centre of Future Urban Design, Beijing University of Civil Engineering and Architecture, Beijing 100044, P. R. China*

Mark C. M. van Loosdrecht – *Sino-Dutch R&D Centre for Future Wastewater Treatment Technologies/Beijing Advanced Innovation Centre of Future Urban Design, Beijing University of Civil Engineering and Architecture, Beijing 100044, P. R. China; Department of Biotechnology, Delft University of Technology, 2629 HZ Delft, The Netherlands;* orcid.org/0000-0003-0658-4775

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.est.4c05903

Notes

The authors declare no competing financial interest.

Biography

Dr. Xiaodi Hao is now a full professor at Beijing University of Civil Engineering and Architecture, China. He is an editor of *Water Research*, appointed July 2009. He earned his B.S. at Taiyuan University of Technology, China, his M.S. at the Harbin Institute of Technology, China, and his Ph.D. at Delft University of Technology, The Netherlands. He worked in The Netherlands (TU Delft and TNO), France (CEMAGREF), Hong Kong (Poly-U and UST), United States (Auburn University), and Japan (Gifu University) for eight years. His research interests focus on sustainable biological wastewater treatment and resource recovery (especially recovery of phosphate and energy). He has written and published six books in Chinese and two books in English as well as more than 120 international and 210 domestic papers.

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