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CHAPTER 1

Resource recovery from wastewater: historical context, drivers, and global perspectives

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In the past century, wastewater treatment (WWT) has undergone a significant transformation, based on a growing understanding of environmental processes and, therefore, increasing regulatory demands. Initially, the primary objective of WWT was the removal of pathogens and improvement of human health in cities. Additionally, the removal of organic matter prevented oxygen depletion in receiving water bodies. That is why the early activated sludge systems were designed for suspended solids and chemical oxygen demand (COD) removal. Nutrient removal occurred incidentally due to assimilation into microbial biomass.

In the 1980s, attention shifted toward the removal of nitrogen (N) and phosphorus (P), primarily driven by a growing understanding of how elevated concentrations of these nutrients contribute to eutrophication. Regulating bodies reacted to this knowledge by formulating guidelines on nutrient removal. In the Europe Union (EU), the Urban Wastewater Treatment Directive (91/271/EEC), adopted in 1991, marked the first harmonized legal framework for WWT across member states, mandating N and P removal in designated sensitive areas (Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment, 1991). In the United States, nutrient control was addressed through the Clean Water Act and the National Pollutant Discharge Elimination System (NPDES) permits (US Environmental Protection Agency, 2025). Additionally, China (Li and Yu, 2025) and India tightened effluent standards in response to severe water quality degradation.

Technological responses to stricter legislation included the extension of the activated sludge systems with nitrification, oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), followed by denitrification, NO_3^-, and reduction to dinitrogen gas (N_2). Phosphate was removed by chemical precipitation using iron or aluminum salts. At the same time, the discovery of phosphate-accumulating organisms (PAOs) enabled the development of enhanced biological phosphorus removal (EBPR) systems, such as the University of Cape Town (UCT)

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configuration, which combined anaerobic, anoxic, and aerobic zones to optimize biological nutrient removal.

With increasing pressure on water systems, for example, due to changing rainfall patterns and excessive water use, the need for stricter discharge limits for N and P is evident (European Parliament and Council of the European Union, 2024). In response, regulatory frameworks are being strengthened and newly implemented across the globe. For example, the recast Directive (EU) 2024/3019 mandates tertiary treatment for all agglomerations above 1000 population equivalents (p.e.) and sets maximum effluent concentrations for larger wastewater treatment plants (WWTPs >150,000 p.e.) at 8 mg/l for total nitrogen (total-N) and 0.5 mg/l for total phosphorus (total-P). China set national limits of ≤15 mg/l for total-N, ≤5 mg/l for ammonium, and ≤0.5 mg/l for total-P, as well as even lower limits in sensitive regions (Li and Yu, 2025).

The trends for strict effluent demands on N and P give rise to the need for and development of innovations for the secondary and tertiary treatment of wastewater. At the same time, broader sustainability goals are leading to a more circular economy. This paradigm shift—from removal to recovery—has also been adopted by WWT innovators: researchers and practitioners recognize that nutrients in wastewater are not just pollutants to be removed, but are valuable resources. Nutrient recovery, particularly of P and N, offers opportunities to reduce dependence on finite mineral resources, lower greenhouse gas emissions, and create new economic value from waste streams. This book offers theoretical insight and inspirational examples of trends in these developments for current and future WWT practices. In this introduction, we briefly analyze recent developments and need for additional research.

1.1 The N-cycle and the N_2O problem

In recent years, our understanding of the nitrogen (N) cycle is growing rapidly due to the increasing availability of high-end analytical techniques, including integrated sequencing and multiomics approaches, revealing great complexity. Besides an extensive ecosystem of syntrophic and otherwise interacting microorganisms, different pathways can even coexist within the same microorganism (Chapter 2). Whereas conventionally N removal was categorized into nitrification and denitrification, the discovery of ammonium-oxidizing archaea (AOA), anaerobic ammonia oxidation (anammox), and organisms oxidizing ammonia completely to nitrate (comammox) has radically broadened our understanding of the global nitrogen balance. Additionally, the current knowledge that many microorganisms perform only some denitrification steps (partial denitrifiers), rather than completing the entire pathway (complete denitrifiers), and the discovery of dissimilatory nitrite reduction to ammonia (DNRA) underline the complexity of N removal in WWT systems (Roothans et al., 2025a).

The deeper understanding of the conversions in the N-cycle also slowly unravels the causes of the observed N_2O emissions from WWTPs. N_2O is a major ozone-depleting substance and a greenhouse gas, 273 times stronger than CO_2. Its emissions can account for up to 80% of a WWTP's carbon footprint, counteracting the current expensive efforts to fulfill the aim of climate-neutral WWT (Daelman et al., 2015). This highlights the urgent need to understand the underlying microbial mechanisms that drive these emissions. Current understanding, however, shows that the coexistence of multiple microbial nitrogen pathways results in process conditions that variably trigger N_2O emissions, often in opposing ways, complicating emission control strategies. For example, N_2O is emitted during nitrification under high oxygen and high ammonia, as well as by nitrifier denitrification when oxygen concentrations are low and nitrite concentrations are high. Heterotrophic denitrifiers release N_2O as an intermediate when COD concentrations are low or oxygen concentrations are high. Besides, abiotic reactions can produce N_2O in presence of metallic ions. To date, the operational and metabolic mechanisms controlling seasonal N_2O emissions remain largely unknown, hindering effective mitigation (Roothans et al., 2025b).

1.2 Addressing organic nitrogen and phosphorus in effluent

With increasingly stringent effluent discharge limits for total-N and total-P, WWTPs must go beyond conventional nitrification, denitrification, and orthophosphate removal. A substantial portion of total-N and total-P in effluent, up to 30%–60% in advanced biological nutrient removal systems (WRF The Water Research Foundation, 2019), consists of soluble and often recalcitrant organic N and P. The implementation of thermal hydrolysis processes (THP) to enhance anaerobic digestion and produce Class A biosolids leads to the formation of melanoidins, persistent organic compounds that accumulate in reject water and are recycled to the waterline, contributing to overall nutrient loads. These melanoidins also interfere with phosphate crystallization, jeopardizing recovery efforts (Pavez-Jara et al., 2024).

The speciation and bioavailability of organic nutrient fractions remain poorly understood, complicating modeling and control strategies. Moreover, analytical methods for low-level and online detection require further development. Innovations targeting efficient and cost-effective biodegradation or separation of organic nutrients are essential to meet regulatory demands. Technologies developed for effluent polishing and micropollutant removal—such as advanced oxidation, adsorption, and membrane filtration—may offer potential, but their performance can be compromised when simultaneously targeting organic nutrients. Electrocoagulation, for example, has shown promising results, but its effectiveness is limited under variable operational conditions and requires further optimization (Koyuncu and Arıman, 2020).

1.3 Beyond removal: drivers for nutrient recovery

Stricter effluent guidelines and the aim for climate-neutral WWT force us to rethink biological WWT. The attention for nutrient recovery from sewage has increased dramatically since the beginning of this century. From a few publications in the early 2000s, mainly describing the advantages of anaerobic digestion, decentralized sewage treatment, and source separation, nowadays over 150 scientific papers on nutrient recovery from sewage are published yearly, describing a broad range of innovations and applications from laboratory experiments to full-scale resource recovery WWTPs (Scopus, 2025). This is fully in line with the paradigm shift toward viewing wastewater as a mine of recoverable resources during the past decade(s), supported by international organizations such as the International Water Association (IWA, 2022) and the United Nations Environment Programme (UNEP).

Many nutrient recovery technologies are technically feasible and have reached maturation (Chapters 16–21). However, given the relatively low price of commodity fertilizers, they are often not yet economically compelling. Market value chains for recovered products are still underdeveloped, and questions of social acceptance and regulatory frameworks require careful attention (Kehrein et al., 2020). Moreover, the dilute nature of municipal wastewater means that recovery is often energy-intensive unless complemented by separation or concentration strategies. These hurdles emphasize the importance of interdisciplinary approaches, linking engineering, microbiology, economics, and policy, to unlock the full potential of nutrient recovery.

1.4 From removal to recovery

This book presents a range of perspectives on the evolution of WWT systems with respect to nutrient removal, recovery, and reuse. It documents current practices and emerging approaches being explored globally. Chapters 2–4 revisit the core principles of biological nitrogen and phosphorus removal, and the microbiology that drives them. Natural and decentralized systems (Chapters 5–7) and novel and established biological approaches (Chapters 8–15) highlight how context and scale shape solutions and lead to innovations. Chapters 16–20 explore advanced resource recovery strategies, such as ammonia upcycling, bio-electrochemical systems, and biorefinery concepts. The final chapter (21) addresses sustainability assessment, emphasizing the need to evaluate innovations within their environmental, economic, and social context. This book underlines the growing recognition that nutrient removal and recovery are key to building a sustainable future and that there is a need for transformation of WWTPs into water resource recovery facilities, as understanding is growing and technologies mature, while acknowledging the complexity that still surrounds implementation.

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