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Path to Carbon Neutrality in Wastewater Treatment—From Energy Optimisation to Resource Recovery

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ABSTRACT

Related to the global efforts to minimize climate change, wastewater treatment plants (WWTPs) face increasing pressure to minimize energy use and achieve carbon neutrality. This requires a multifaceted approach: First, energy consumption must be minimized through enhanced energy efficiency in existing WWTPs and the adoption of low-carbon technologies, such as anammox-based processes, aerobic granular sludge, and membrane aerated biofilm reactors. Second, reducing greenhouse gas emissions, particularly nitrous oxide, is as critical as improving energy efficiency. Third, energy recovery should extend beyond conventional methods like anaerobic digestion or sludge incineration to include harnessing effluent heat from treated wastewater. Finally, resource recovery—encompassing nitrogen, phosphorus, and biopolymers—offers greater societal value than energy independence alone. This article critically reviews strategic pathways to achieving carbon neutrality in wastewater treatment, which brings together energy efficiency, greenhouse gas emissions, and energy and resource recovery within a single framework.

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1. Introduction

Wastewater treatment plants (WWTPs) primarily aim at removing pollutants such as organic carbon, nitrogen, and phosphorus compounds from wastewater to protect human health and the environment. Additionally, in response to the global energy crisis and climate change challenges, optimizing energy use and reducing carbon emissions have become critical priorities. These priorities are translated into goals such as “achieving carbon neutrality” and “reaching net-zero” processes [1].

Carbon neutrality can be seen as a balanced state in which carbon emissions are reduced and offset so that their net contribution to the atmosphere is zero. The carbon emissions from WWTPs mainly comprise direct greenhouse gas emissions (Scope 1), energy-related carbon emissions (Scope 2), and other indirect emissions, such as chemical addition and waste sludge disposal (Scope 3) [2]. The goal of carbon neutrality in WWTPs can be

achieved by eliminating or at least minimizing the emissions across all three scopes (Fig. 1).

During wastewater treatment, a significant energy input is required for aeration, mixing, and pumping purposes (Scope 2 emissions). Meanwhile, strong greenhouse gases (GHG) are produced in the treatment process (Scope 1 emissions). More specifically, the conversion of nitrogen compounds entails the production of N_2O , a very strong greenhouse gas which has been identified as a major contributor to the overall carbon footprint of WWTPs [3,4]. Sludge digestion results in biogas production, which can be valorized as energy, but at the same time, the associated sludge treatment train brings along methane emissions, which even risk to offset the carbon dioxide emission that is avoided by using the resulting biogas for energy generation [5]. Overall, while meeting effluent quality requirements remains the prerequisite, energy optimization and GHG emission reduction are equally important objectives for WWTPs.

Various options for energy recovery in the form of biogas or heat are available, reducing the Scope 2 (for energy used on-site) or Scope 3 (energy injection into the grid) emissions. As a next step, the organic carbon, nitrogen, and phosphorus present in

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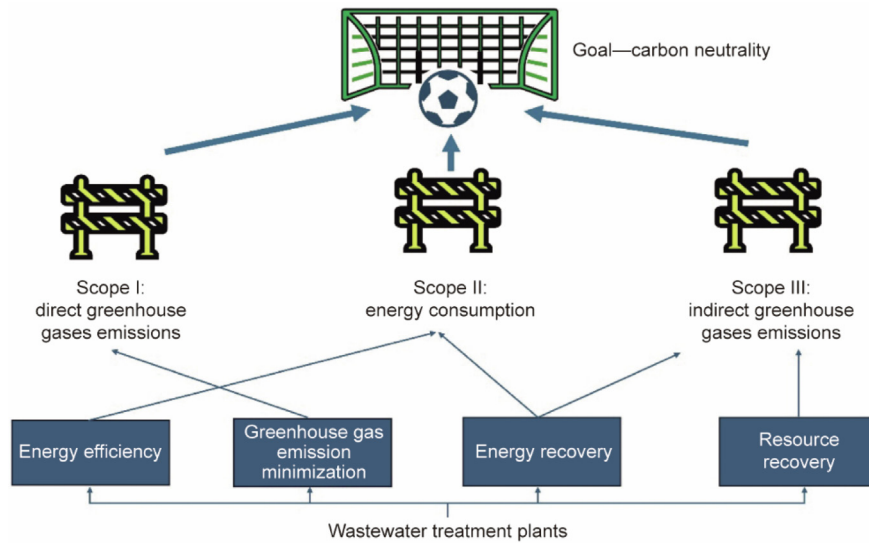


Fig. 1. Reaching carbon neutrality in wastewater treatment plants by acting on the different scopes through energy efficiency, greenhouse gas emission minimization, energy recovery, and resource recovery.

wastewater also represent opportunities for the recovery of other resources. Recovery of organic compounds may compete with energy production at the WWTPs in the form of biogas. However, recovery of nutrients and chemicals from wastewater can minimize the overall carbon emissions in society when they replace fossil oil-based products, thus impacting Scope 3 emissions.

This contribution outlines a roadmap toward carbon neutrality in WWTPs, highlighting energy efficiency optimisation, greenhouse gas emission reduction, energy recovery, and resource recovery as the milestones.

2. Energy efficiency

Energy efficiency can first of all be achieved by reducing energy use in existing WWTPs. As a next step, novel low-carbon treatment processes could be introduced, either by building new plants or retrofitting the existing ones (Fig. 2).

2.1. Optimising existing WWTPs

While building new plants is likely to attract public attention and recognition, optimizing existing plants is more essential and more urgently needed. Given that there are more than 109 000 WWTPs worldwide, serving 2.7 billion people [6], it is clear that a huge amount of energy could be saved by optimizing existing plants. The experience gained could be subsequently used for constructing new plants.

Energy consumption in a typical WWTP is predominantly driven by aeration (50% to 60% of the total energy consumption), pumping (around 15% of total energy consumption), and sludge treatment (15% to 25% of total energy consumption) [7]. Optimization of existing WWTPs can be achieved through implementing good monitoring systems combined with smart process control strategies, which minimize energy consumption. Aeration control is the most important, as aeration represents the largest share of energy consumption. The aeration intensity may be controlled through fixed or ammonium-based dissolved oxygen setpoint control, following simple or more advanced control algorithms (see Refs. [8,9] for an illustrative example). Variable speed drive compressors can reduce the energy consumption of the blowers, providing the required aeration flow rate. Pumping energy may be minimized by adapting the sludge recycle ratio based on the influ-

ent wastewater characteristics and denitrification needs. Additionally, the energy efficiency of pumps may be increased by adjusting their rotational speed to match the system's changing load, for instance, due to changing sludge composition [10].

When optimising WWTP operation, it is important to realize the trade-off between effluent quality on the one hand and energy input and associated costs and CO₂ emissions on the other hand. For highly sensitive receiving water bodies, stricter discharge standards may be necessary, even though this inevitably leads to higher carbon emissions. Conversely, for less sensitive water bodies, more relaxed discharge standards may be appropriate, since the energy consumption increases more than proportionally with effluent quality improvement. Moreover, regional development status should also be considered, as the implementation of stringent discharge standards may entail a significant increase in treatment costs, which may not be feasible for some developing countries.

2.2. Novel low-carbon treatment processes

An essential development is a novel low-carbon treatment process, prioritizing reduced energy demand associated with aeration, pumping, and sludge treatment operations. Currently, various novel low-carbon treatment processes have been developed, such as anammox-based process, aerobic granular sludge (Nereda), and membrane aerated biofilm reactor (MABR).

2.2.1. Anammox

The anammox process, converting ammonium and nitrite to nitrogen gas, is one of the most promising next-generation wastewater treatment processes [11]. In this process, only 50% of the ammonium needs to be converted to nitrite, implying savings of about two-thirds of the energy consumption for aeration, in comparison with conventional nitrogen removal through nitrification–denitrification (Table 1). Thanks to the autotrophic nature of anammox bacteria, organic carbon is not required and can be saved for resource recovery processes.

Anammox-based processes are well-established for sidestream treatment of municipal wastewater [12] and high-strength industrial wastewater [13], but their application in mainstream wastewater treatment remains under exploration [14,15]. Mainstream anammox has been reported to occur unintentionally. For instance,



Promoting energy efficiency in WWTPs

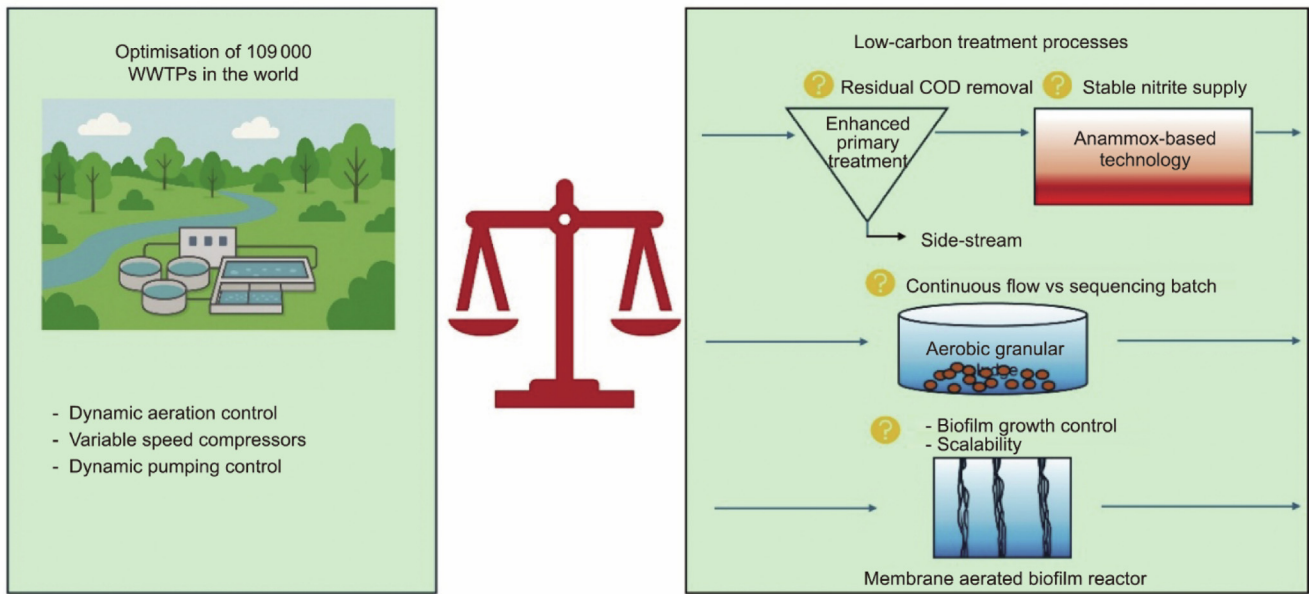


Fig. 2. Promoting energy efficiency in WWTPs by optimising existing plants and adopting novel low-carbon treatment processes.

Table 1

Plant-wide energy consumption and energy saving estimation of low-carbon treatment processes compared to conventional activated sludge processes.

Process	Energy consumption (kW·h·m ⁻³)	Energy saving potential (%)	Type of energy saved	Reference
Conventional activated sludge	0.2~2.0*	reference case	—	[21–23]
Partial nitrification anammox	0.1~0.5**	73	Aeration for nitrification; sludge treatment	[24]
Partial denitrification anammox	Not found	~50	Aeration for nitrification; sludge treatment	[25]
Aerobic granular sludge	0.22	~20	Pumping	[26]
Membrane aerated biofilm reactor	0.1–0.2	~80	Aeration	[27]

* The energy consumption can be largely affected by regional conditions (influent characteristics, temperature, and discharge regulation).

** The data were collected without considering the recovery energy from the biogas system.

in a full-scale wastewater treatment plant (WWTP) operating with hybrid biofilm/suspended growth at moderate temperatures under microaerophilic conditions induced by air scouring [15].

Challenges in mainstream anammox application lie in the anammox-based process itself, especially in the nitrite supply processes, such as partial nitrification or partial denitrification, as well as in achieving stable and effective organic carbon removal beforehand.

Nitrite supply for mainstream anammox is typically hindered by the complexity of process control, low temperature, and variable influent loads. A conventional single parameter control (e.g. dissolved oxygen) has been proven unreliable for achieving main-stream nitrite supply, where a combined and smarter control strategy needs to be developed, by identifying the niche differentiation of the species in the system [16]. As for low-temperature issue, an acclimatized sludge (temperature gradually lowered) can have much higher tolerance to low temperature than the sludge directly taken from a high-temperature operated reactor [17]. The challenge from variable influent loads mainly comes from the organic carbon.

Residual organic carbon complicates nitrification control, as the oxygen is preferentially consumed by ordinary heterotrophic organisms before it becomes available to the ammonium oxidising bacteria. This in turn leads to the washout of autotrophic bacteria,

such as ammonium oxidizing bacteria and anammox bacteria, which grow slowly at low temperatures [18,19]. Moreover, energy savings from anammox require integration with effective organic carbon recovery technologies [20], not just the anammox process alone. These processes get relatively little attention compared to anammox processes. Enhanced primary treatment methods, such as chemically enhanced primary treatment and high-rate activated sludge processes, are well-suited for pairing with anammox. These approaches not only recover organic carbon but also improve anammox performance by reducing organic carbon loads. The organic carbon removal stage remains the main bottleneck in an enhanced primary treatment-coupled anammox process, as unstable operation in this stage can disrupt the subsequent anammox-based treatment [18].

2.2.2. Aerobic granular sludge

Aerobic granular sludge (AGS) technology has gained widespread attention in the worldwide wastewater treatment field under the trademark Nereda. It has brought new life to sequencing batch mode wastewater treatment through rapid separation of sludge and water. In comparison with the continuous-flow activated sludge process, AGS in batch mode can reduce about 30% of energy consumption (Table 1), mainly due to the minimisation of mechanical energy needs (no need for pumping, mixers, or

clarifiers with moving bridges). From a construction perspective, AGS significantly reduces land use for the reactors, with up to 75% compared to activated sludge systems, due to its compact sludge form and high treatment capacity [28]. Additionally, a dynamic profile of pollutant removal can be obtained via monitoring a sequencing batch reactor, which allows for a more effective process optimization with respect to nutrient removal and energy efficiency. The constant volume maintained in the Nereda technology eliminates the need for a moving decanter, which is one of the bottlenecks of conventional SBR processes.

Although AGS is preferably implemented in sequencing batch mode [29], most existing WWTPs operate under continuous flow mode, which makes it difficult to retrofit. Notably, when AGS is applied to an existing WWTP under continuous flow mode, it can still improve the sludge settleability and allow for a higher loading rate [30,31]. However, it is important to acknowledge that AGS also entails increased diffusion limitation compared to activated sludge, which risks negatively impacting the aeration energy consumption when operating at relatively high DO levels [32]. It is therefore important to adjust process operation in order to fully benefit from AGS introduced in continuous wastewater treatment plants. Another potential solution for upgrading existing continuous activated sludge plants could be a hybrid sequencing batch-wise AGS system in parallel with a conventional activated sludge process. In that way, the plant needs minimum changes, but still benefits from the profits of the AGS process [28].

2.2.3. Membrane aerated biofilm reactor process

Over the last two decades, membrane-aerated biofilm reactors (MABR) have emerged as a new technology. In this type of reactor, oxygen is directly supplied through one side of a hydrophobic membrane, while biofilm grows and attaches to the opposite side immersed in the wastewater [33].

MABRs are able to effectively enhance oxygen transfer efficiency through the counter-flow between oxygen and dissolved substrates. Since no bubble formation is needed, oxygen transfer can be achieved at lower energy costs, thus realizing significant savings in aeration energy, which is the predominant energy consumer in WWTPs. The oxygen transfer efficiency in MABRs is theoretically able to reach 100% (compared to 4%–30% in conventional aeration), leading to an aeration efficiency of 5–20 $\text{kgO}_2/(\text{kW}\cdot\text{h})^{-1}$, compared to 1–5 $\text{kgO}_2/(\text{kW}\cdot\text{h})^{-1}$ with conventional aeration methods [34]. Based on the above data, taking into account that the average aeration efficiency of MABR (12.5 $\text{kgO}_2/(\text{kW}\cdot\text{h})^{-1}$) is five times of conventional aeration methods (2.5 $\text{kgO}_2/(\text{kW}\cdot\text{h})^{-1}$), the energy consumption for aeration can be reduced by about 80% (Table 1), leading to total energy savings of 40%–50% at the level of the WWTP. Currently, MABRs have been implemented on full-scale, by several vendors worldwide [35].

Meanwhile, there are also some challenges hampering the full-scale implementation of MABRs. A primary technical challenge lies in the biofilm growth control, in terms of thickness and layer distribution [35]. Furthermore, the scalability of MABRs constitutes a practical challenge due to the lack of guidelines as well as a financial challenge in terms of high pumping and pressurizing costs [36].

As a final note, the selection of low-carbon technologies can also be affected by regional conditions, particularly local temperature and the composition of wastewater. For instance, autotrophic-based bioprocesses (e.g., partial nitrification/anammox (PN/A)) require less effort in temperature control in warm regions and in wastewater with low organic carbon, whereas granular sludge systems (e.g., Nereda) hold greater resilience in cold regions and fluctuating influent loads.

3. Greenhouse gas emission minimization

Methane and nitrous oxide are two very strong greenhouse gases produced during wastewater treatment, the respective global warming potential of which is 30 and 273 fold stronger than that of carbon dioxide over a 100 year horizon [37]. Thus, reducing direct carbon emissions in the form of greenhouse gases is an equally important goal alongside minimizing energy consumption. The carbon footprint of WWTPs without anaerobic digestion is dominated by electricity consumption, whereas methane emissions will have a major contribution to the carbon footprint for WWTPs with anaerobic digestion. The share of N_2O in the carbon footprint of a WWTP is most variable and highly dependent on the plant design and operation, but may take up to 80% of the overall carbon footprint [38].

For a WWTP equipped with anaerobic digestion, the largest share of methane emission (about 75%) comes from the thickeners, dewatering unit, and sludge buffer tanks, with around 5%–10% of methane produced during anaerobic digestion emitted to the air [4]. As a result, the carbon credits earned by biogas utilization may be overruled by the methane emissions. There are some ways to control methane emissions after anaerobic digestion, such as using the ventilation air from the buffer tank as combustion air in the engines of the cogeneration unit [4]) and thermal drying of the digested sludge, preventing the methanogens from further producing methane [39]. Besides the methane emissions originating from sludge treatment, a significant amount of methane is present in the influent wastewater and may be either stripped or biologically oxidized in the aerobic activated sludge tanks—the latter may be promoted by adequate process design and optimization [40].

Nitrous oxide emissions are highly variable due to complex microbial pathways involved in its production [3]. Nitrification has been found to be the main source of nitrous oxide production in wastewater treatment, while denitrification may contribute to reducing nitrous oxide emissions by its reduction to nitrogen gas [41]. It is worth noting that nitrite presence is correlated to nitrous oxide emissions [3]. Given that the anammox conversion relies on nitrite production by either partial nitrification or partial denitrification, nitrous oxide is emitted from the nitrite supply of anammox-based processes. Reported values for nitrous oxide emissions from anammox-based processes are highly variable [42]. For future applications, it would be essential to find measures to minimize the emission of this strong greenhouse gas. So far, even though there have been a lot of efforts into the study of nitrous oxide emissions, with regard to influencing factors and reaction mechanisms, it is still not really possible to predict the nitrous oxide emissions, especially in the long-term [37]. Still, even without accurate long-term predictions, models have proven their worth in developing mitigation strategies. For instance, Ref. [43] successfully applied model simulation results in defining N_2O mitigation strategies based on lowering dissolved oxygen concentrations to specific setpoints, resulting in 35% N_2O emission reduction upon full-scale implementation.

4. Energy recovery

The idea of energy recovery from WWTP is to identify and utilize the energy stored in wastewater. There are two ways of producing energy from wastewater: The first one is to recover energy from the sewage sludge, the main by-product of wastewater treatment, while the second one is to directly recover heat from the wastewater itself. The recovered energy could either be used to support the on-site operation of the plant or supplied to the local community.

4.1. Energy production from sewage sludge

4.1.1. Anaerobic digestion coupled with biogas upgrade

Anaerobic digestion has been commonly applied already in very early WWTPs to stabilize the sewage sludge (volume reduced by around 30%), and it is still used in modern WWTPs due to the increasing demand for energy supply. The energy supply is done by burning the biogas in a boiler for heat production or in a cogeneration unit for combined electricity and heat production. The latter is often more attractive due to local subsidy programs.

In the development process of anaerobic digestion, many approaches have been proposed to enhance biogas production and thereby increase energy generation. These include pretreatment of waste activated sludge to improve digestibility [44], as well as co-digestion with food waste to provide additional organic load [45]. However, pretreatment methods are generally limited by their high costs and energy consumption, entailing a negative impact on the overall carbon footprint. Also, adding food waste to the digester is not really a way of achieving energy neutrality since the input food waste should be seen as an input of external energy. Moreover, the extra food waste generates an increased nutrient load in the reject water, the treatment of which often offsets the extra energy production from the food waste.

As an alternative to using the biogas in a cogeneration unit to produce electricity, the biogas (roughly containing 50%–60% methane and 40%–50% CO₂) can be upgraded to so-called biomethane. Biogas upgrading is mainly achieved by either physico-chemical methods, including water scrubbing, membrane or cryogenic separation, or biological methods (*in-situ* or *ex-situ*) [46]. The biomethane typically contains over 90% methane, with relatively few impurities. It can be marketed as a commercial product by injection into the gas grid, even though often only economically advantageous when subsidized. The required heat to keep the anaerobic digester temperature can, in this case, be provided through a heat pump; the electricity from photovoltaic panels on site.

Overall, achieving energy-neutrality or even having a surplus amount of energy is often mentioned as a goal of anaerobic digestion facilities in WWTPs. But so far, there have been hardly any plants disconnected from the electricity grid. The latter would be a true cost saving measure for the WWTP [47].

4.1.2. Incineration

Incineration of sewage sludge directly converts the biomass into heat and reduces the volume of organic waste almost completely. To get an optimal heat production, the sludge should be almost completely dried, which can be achieved either through the use of effluent heat [48,49], solar drying, or in a dry-composting installation [50]. The caloric value of dried sewage sludge is comparable to brown coal (lignite) and can be co-fueled in a coal fired power plant. In case the end disposal solution of sewage sludge is incineration, applying preceding anaerobic digestion is questionable. Both technologies can recover the energetic value of the sludge, but both also require additional energy input for process operation. While both anaerobic digestion and direct incineration produce similar amounts of energy, the direct incineration process requires less energy input and has lower investment and operational costs than a combined process [51]. In this way, the benefits of the produced energy extend beyond the WWTPs themselves, as the recovered heat can also be supplied to external district heating networks for households or industrial use [51].

Sludge incineration may take place as a co-fuel, for instance, in the cement industry or along with industrial waste. However, mono-incineration of sludge offers more potential for the recovery of nutrients—such as phosphorus—from the ash. Smart localization of the incineration facility allows to make optimal use of the

energy produced. A nice example is the location of a mono-incinerator close to a steel-production company in the region of Flanders, Belgium, where the dried sludge will be burnt for maximising energy and phosphorus recovery.

4.2. Heat recovery from effluent wastewater

The effluent heat of WWTPs is often neglected but has a vast potential for energy production. The yearly energy recovery potential for effluent heat is estimated to be 25–30 times larger than that for biogas usage on the same wastewater treatment plant [51]. The effluent wastewater could be delivered to the heat pump, which produces heat for the community in winter, while delivering cooling capacity in summer. Alternatively, heat could be stored in summer if there is a suitable aquifer below the treatment plant. In order to be able to profit from an effluent heat recovery system, it should be attached to a district heating (or cooling) network close to a residential area.

The carbon credits resulting from heat recovery, be it from the effluent wastewater or through incineration, are typically taken by the heat recovery company or energy utility outside the fence of the WWTP and not by the WWTP owners—even though such practices may be country-specific. For society as a whole, there is no difference, but it takes away a bit of the incentive for such projects by water utilities.

5. Resource recovery

In recent years, a shift from WWTP to water resource recovery facilities has been emphasized. In this context, conventional pollutants, namely organic carbon, nitrogen, and phosphorus, in wastewater are regarded as resources to be recovered, besides the clean water as the prime resource [52].

In typical WWTPs, 40%–50% of the influent COD is oxidized in the main-stream units, around 10% of the influent COD remains in the effluent, and the rest is incorporated into sludge [53], which is the fraction that can potentially be taken advantage of for resource recovery. However, the organic carbon in the wastewater can be used only once, such as, either recovered as energy or converted into chemical products. Hence, there is a trade-off between energy recovery and producing chemicals.

According to Ref. [54], energy recovery from wastewater could only meet around 1% of the national energy demand, a number which is almost negligible. But the recovery of chemicals has remarkable economic benefits. For instance, with 3 kg of COD, 1 kg of bioplastic can be made and sold at 5 EUR, compared with methane sold at 0.1 to 0.6 EUR·m⁻³, depending on the level of subsidy. In addition, these bio-produced chemicals are, in general, more environmentally friendly than oil-based alternatives. In the end, converting organic carbon in wastewater into chemical products will be more beneficial for society. Moreover, recovered chemicals can still be burned after use for energy generation. The organic carbon in wastewater can be converted into chemical products and recovered in the forms of cellulose, biopolymers (e.g. Kaumera), volatile fatty acids, polyhydroxyalkanoate, and carbon dioxide [55]. The costs of product recovery from the diluted streams are often a limitation, therefore, it is useful to focus on easy recoverable products such as polymers. For instance, polyhydroxyalkanoates (bioplastics) or extracellular polymers (hydrocolloid) are currently in the process of being scaled up to full scale applications [56–58]. The key technical challenges of bioplastics recovery lie in the enrichment of polyhydroxyalkanoates within sludge [59] and the subsequent extraction [60]. Looking ahead, selecting dedicated microbial strains with high PHA storage capacity may maximize recovery potential. In parallel, advancing PHA

extraction technologies—particularly with respect to solvent recycling and extraction efficiency—will be essential steps toward large-scale application.

Anaerobic digestion of sewage sludge is preferable when the digestate can be used for fertilization of agricultural lands since the nutrients (N and P) are retained in the digestate. However, land use of digestate has been constrained by regional policies in many countries. As a result, additional steps are needed to recover the nutrients from the digestate, such as chemical leaching, which is less ideal due to the complexity and additional cost of the recovery process [61].

6. Conclusions

Reaching carbon neutrality in wastewater treatment can be achieved by playing on different levels. While some of them may get less public (media) and research attention than others, that does not make them less impactful. More attention should be put on energy minimization in existing WWTPs through smart control, such as on aeration and sludge pumping/treatment. When it comes to building new WWTPs or retrofitting existing ones, the focus should go to novel low-carbon treatment processes. Anammox and MABR technologies mainly save on aeration energy, while AGS savings mainly result from lower pumping costs. Minimizing the direct emission of methane and N₂O as strong greenhouse gases is equally important as minimizing CO₂-emissions from energy consumption. Methane emissions may best be reduced by acting upon the sludge treatment units or completely omitting anaerobic digestion. Nitrous oxide emissions may be reduced through adequate process design and operation, although there are no clear general guidelines in this respect. When it comes to energy recovery, biogas production is overvalued, whereas effluent heat has often been neglected. Resource recovery, like bio-produced chemicals, may have more added value than the energy neutrality of the plants.

CRediT authorship contribution statement

Bohan Yu: Writing – review & editing, Writing – original draft. **Eveline I.P. Volcke:** Writing – review & editing, Supervision. **Xiaodi Hao:** Writing – review & editing. **Mark C.M. van Loosdrecht:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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