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Review

# Anaerobic microbial core for municipal wastewater treatment — the sustainable platform for resource recovery

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The requirement for carbon neutrality and bioresource recovery has shifted our views on water treatment from health and pollution avoidance to one of sustainability with water and nutrient circularity. Despite progress, the current process of wastewater treatment is linear, based on core aerobic microbiology, which is unlikely to be carbon neutral due to its large use of energy and production of waste sludge. Here, we outline a shift from aerobic to anaerobic microbiology at the core of wastewater treatment and resource recovery, illustrating the state-of-the-art technologies available for this paradigm shift. Anaerobic metabolism primarily offers the benefit of minimal energy input (up to 50% reduction) and minimal biomass production, resulting in up to 95% less waste sludge compared with aerobic treatment, which is increasingly attractive, given dialogue surrounding emerging contaminants in biosolids. Recent innovative research solutions have made ambient (mainstream) anaerobic treatment a ready substitute for the aerobic processes for municipal wastewater in temperate regions. Moreover, utilising anaerobic treatment as the core carbon removal step allows for more biological downstream resource recovery with several opportunities to couple the process with (anaerobic) nitrogen and phosphorus recovery, namely, potential mainstream anaerobic ammonium oxidation (anammox) and methane oxidation (N-DAMO). Furthermore, these technologies can be mixed and matched with membranes and ion-exchange systems, high-value biochemical production, and/or water reuse installations.

As such, we propose the reconfiguration of the wastewater treatment plant of the futurewith anaerobic microbiology. Mainstream anaerobic treatment at the core of a truly sustainable platform for modern municipal wastewater treatment, facilitating circular economy and net-zero carbon goals.

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## Introduction

Despite progress, the provision of clean water and treatment of wastewater remains a pressing global challenge. Clearly highlighted by the United Nations (UN), water is identified as a standalone UN Sustainable Development Goal (SDG 6: Clean Water and Sanitation) and water development underpins the success of many of the other goals: better health (SDG3), sustainable energy (SDG7), and climate action (SDG13), among others. For over a century, the developed world has been built upon linear, aerobic microbiology-based treatment processes, namely, 'conventional activated sludge' (CAS), to clean wastewater to sufficient quality and discharge it back into the environment. This has been highly effective for health and largely for environmental water quality and was deployed as the praxis in the global north. However, it is energy intensive (1–3% of total global energy usage), produces significant waste products (i.e. sludge), and has minimal focus on resource recovery [1–3].

While aerobic microbial treatment, by default, is a linear and carbon emitting process, research developments in the field have focused on improving its resource recovery and water reuse [1]. Nevertheless, such implementations do not meet the requirements of achieving carbon-neutral, energy positivity with resource recovery in a wastewater treatment plant (WWTP), severe changes and innovations are required in the current praxis for the future [4–6].

Therefore, the use of anaerobic microbiology has been suggested as a fundamental alternative at the core biological process of WWTPs [7,8], primarily through mainstream anaerobic treatment, due to lower energy usage and carbon emissions. This change will capture and convert the carbon immediately in the wastewater to biogas, with minimal sludge production (5–10% of aerobic norm) and reduced energy usage (no aeration) of ~50% [5,9]. Proven and implemented at scale in the global south [4,10,11]. It is now feasible at ambient (< 15°C) temperatures and dilute wastewaters, in temperate climates, through successful laboratory and pilot trials, and full-scale demonstrations [12–15]. The results validate large associated merits in sludge reduction and energy input reduction. Furthermore, with carbon-depleted nitrogen (N)- and phosphorus (P)-rich effluent, the process offers a more novel both biological and nonbiological resource recovery and water reuse practices [5].

Here, we detail the current state-of-the-art, options, and perspectives of a recovery-based municipal WWTP based upon an anaerobic (mainstream) treatment as the core technology, therefore providing the paradigm shift required for the *WWTP-of-the-future*.

## Municipal wastewater and aerobic treatment challenges

Municipal wastewaters are dilute (> 99% water), complex, high-volume waste streams arising from domestic sources [16]. Wastewater composition and temperature are highly variable owing to diurnal, seasonal, locality, and infrastructure variances (flow fluctuations of 3× from dry weather flow but up to 6× in 'storm' conditions) [17]. Typically, municipal wastewater can be characterised as dilute by low biological oxygen demand (BOD) and chemical oxygen demand (COD) concentrations (125–350 mg BOD/L) combined with a high fraction of total suspended solids (TSS) and inert particulates (100–250 mg TSS/L) [18,19]. WWTPs ordinarily rely on biological treatment to meet discharge limits for BOD/COD/TSS/Total Nitrogen/Total Phosphorus (e.g. 25/125/25/5/2 mg/l) for certain receiving waters (EU Water Framework Directive, 2000/60/EC and US EPA-821-R13-001).

Currently, during CAS treatment, aerobic microbial consortium degrades the organic fraction of wastewater into carbon dioxide ($CO_2$) and water. In so doing, microbes produce biomass (i.e. sludge), which is settled out, resulting in a high-quality effluent. While CAS meets discharge requirements, the drawback lies in the environmental sustainability of the process: there is a large energy input required to provide oxygen to aerobic microbes (~1.15 kWh/kg BOD) coupled with its production of sludge (0.90–1.25 kg sludge/kg BOD) and a limited capacity for nutrient recovery [5,17,20]. The EU alone produces > 10 million tonnes of waste sludge per year, which is generally treated by a low-rate anaerobic digestion (AD) process followed by land application, or in growing number of countries, incineration [21–23]. This low-rate AD can reduce the amount of biosolids generated by WWTPs (40–60% v/v, depending on thermal hydrolysis usage) and recover some biogas energy [5].

Other technological developments have been made to reduce the negative impacts of CAS, such as granular activated sludge (e.g. Nereda® process), membrane aerated biofilm reactors (e.g. Oxymem®), and modular add-on technologies, such as thermal hydrolysis (e.g. Cambi® process) to assist the low-rate AD process. While these are welcome, the aerobic metabolism remains bound by high energy input and complex by-product (sludge) limiting potential, preventing it to achieve carbon neutrality and offset the WWTP energy demand [24–26].

Furthermore, the pressure to reduce the amount of sludge generated by CAS is increasing as its value as a nutrient recovery system (i.e. biosolid fertiliser) is rapidly reducing, given concerns surrounding land application of biosolids containing chemicals of emerging concern (CECs) such as pharmaceuticals and per- or poly-fluoro-alkylated substances (PFAS). PFAS compounds, for example, found in wastewater, can partition into sludge generated during CAS [27], are not readily removed during AD, and can bioaccumulate when applied to agricultural fields posing a human health risk

[28]; more than half of the biosolids in the United States, Australia, Canada, and Europe are land applied [29]. In fact, several European countries and US states have banned the use of such biosolids [30], effectively revoking their potential for nutrient recovery potential. Furthermore, given that PFAS has been shown to leach from biosolids even when disposed of in landfills, it is likely that high-temperature incineration of biosolids may be required to prevent biosolid-associated PFAS contamination [31]. The regulation and costs of such approaches are likely to scale with waste sludge volume, and reducing this volume should be a key driver in moving away from the aerobic microbiology lead WWTPs.

Other significant climate impacts arise as a result of CAS, including nitrous oxide ($N_2O$) emissions, a greenhouse gas (GHG) that is 298 times more potent than $CO_2$. A recent systems-level assessment reported that $N_2O$ emissions alone can contribute more substantially to the carbon footprint of CAS than its energy consumption [19]. Indeed, it has been suggested that CAS simply transfers water pollution into atmospheric pollution [8]. Transitioning away from aerobic processes would circumvent significant energy expenditures, GHG emissions, and waste biomass production and lead to true resource recovery and valorisation even in the era of emerging contaminants [8,22].

## Advances in anaerobic municipal wastewater treatment

The benefits of a platform with a core of anaerobic microbiology founded in the extremely efficient microbial metabolism. For example, their production of gas as a core output rather than biomass, namely, biogas is produced at up to 0.42 $m^3$ biogas/kg COD (pollution) removed, matched with low biomass production, at 0.05 kg biomass/kg COD removed. This biomass production rate is a reduction of up to 95% compared with aerobic systems [7,9,17].

Such benefits have led to decades of research towards successful implementation across wastewaters processes. While for industrial, concentrated, wastewaters, this has been well established [9]; however, direct sewage treatment has had more limited implementation to date [32].

Save, in tropical climates such as Brazil and India, where full-scale WWTPs of mainstream anaerobic treatment of plants up to 1 million population equivalent are operational. The process is well documented in the following thorough books [10,11].

Implementation outside of tropical climates was largely assumed as unfeasible at lower temperatures (< 15°C) due to increased operational challenges, such as reduced microbial activity and reduced metabolic rates, biomass washout coupled with slow microbial growth rates, methane solubility, and the overall dilute nature of municipal wastewater. However, these issues have been systematically tackled and largely overcome or bypassed through microbiological focus intertwined with engineering in both membrane and nonmembrane anaerobic bioreactors [12,33,34].

Primarily success has been decoupling the solids retention time from the hydraulic retention time (HRT), preventing microorganism washout while continuing to promote high activity, thus enabling high hydrolysis and methanogenesis rates [13,14,35,36].

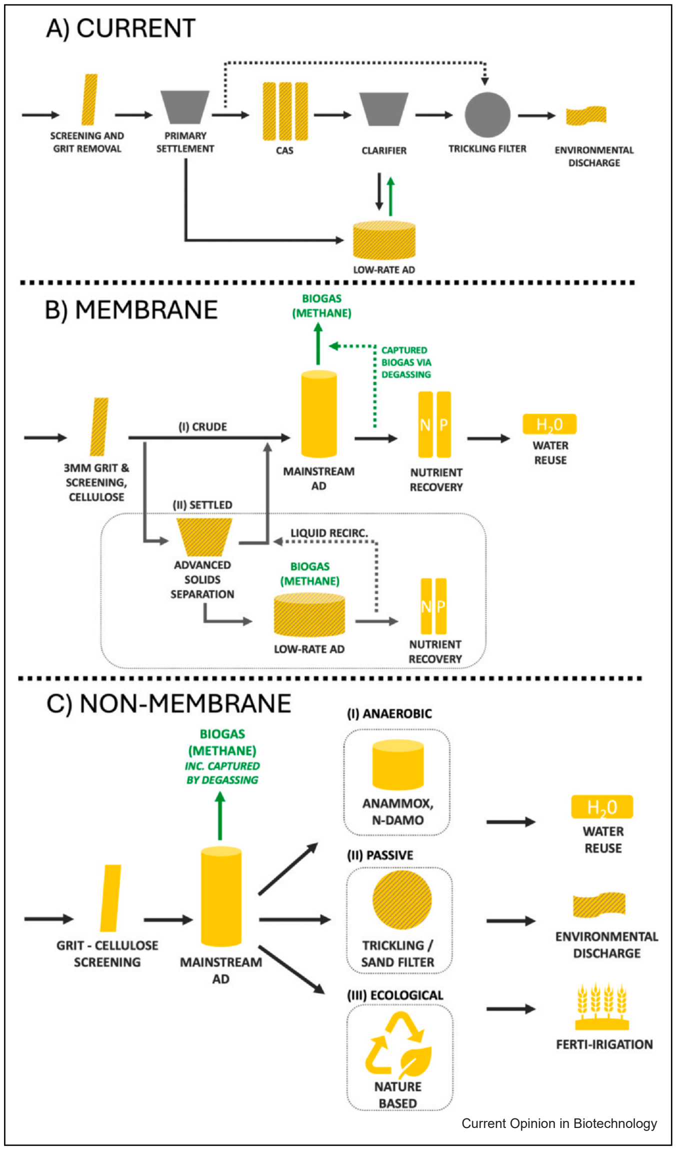
Successes have used different microbial organisations structures, namely (i) granular, (ii) suspended/flocculant, and (iii) biofilms. Granules have been the staple inocula nonmembrane bioreactors (e.g. upflow anaerobic sludge bed or expanded granular sludge bed [EGSB] bioreactors). These are used particularly in the tropical (20°–30°C) [4] and hold potential for lower-temperature Mediterranean (15°–25°C) climate. For more northern temperate climates (< 15°C), granules have generally required tandem biofilms via hybrid systems, successfully outlined in Ref. [14] This system prevented biomass loss and thereby enabled effective COD removals at ambient temperatures (2–20°C) without any membrane filtration. It also demonstrated an ability to withstand seasonal fluctuations in both temperature and influent concentrations.

Whereas more suspended flocculant communities are found in membrane AnMBR systems and have been utilised across temperatures [13,36–38]. Both membrane and nonmembrane systems offer strong options in designing the varied WWTPs that are required across society with examples in Figure 1.

Membrane systems have been shown successfully, in several configurations (anaerobic membrane bioreactors, AnMBRs), including those submerged to reduce flux and 'dynamic membranes' to reduce clogging [32–34]. Notably, AnMBRs can produce a high-quality effluent at short HRT.

Crucially however, in choosing to utilise AnMBR (Figure 2c(ii)) over nonmembrane systems, the additional operational requirements (namely, fouling controls) should be considered [39,40]. However, operational costs can be offset with higher value resources post-treatment, such as more direct water reuse or capture of higher value nutrients. Indeed, these configurations, including membranes, may be preferred where stringent footprint, secondary effluent quality or water reuse is required (e.g. COD < 30 mg/l) due to the

**Figure 1**

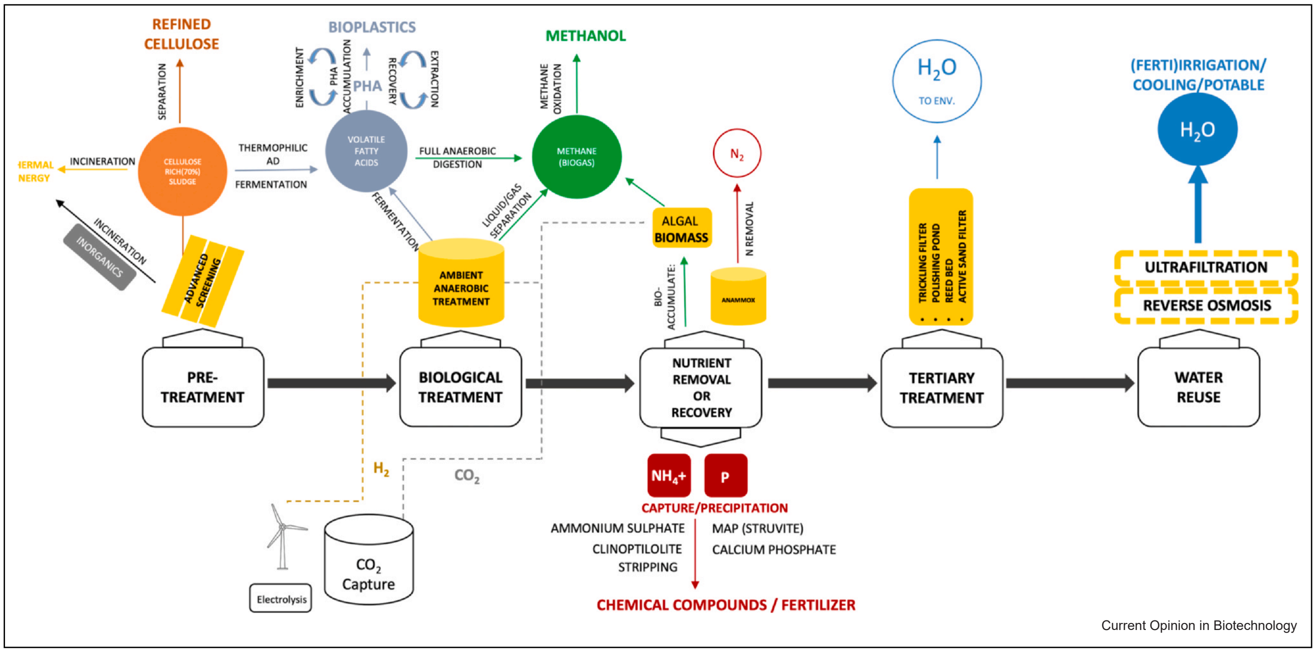



**(a)** Current aerobic-based treatment systems even with technological improvements (technologies in yellow) and low-rate AD treat the wastewater effectively but in a linear manner. **(b)** A membrane-based anaerobic scenario where mainstream AD is inserted to treat the sewage. Two options are outlined **(i)** where the crude sewage is treated by a nonmembrane mainstream AD directly or **(ii)** where advanced/intensive settling or separation (preconcentration) takes place, separating solids from liquid. The solid sewage is treated in an optimised, but low-rate anaerobic manner and liquid and liquid soluble sewage is treated rapidly in a high-rate anaerobic membrane system. The latter step is similar to black-water treatment, which should be reviewed for all new development. The nutrients are then recovered through membrane systems (e.g. IEX) and water is available for reuse. **(c)** A nonmembrane anaerobic system offers more removal-based *WWTP-of-the-future* where resources are recovered where possible or removed biologically by technologies (e.g. anammox/N-DAMO) or through nature-based system, fertiirigation, and water reuse, depending on the WWTP offering passive or energy-limited scenarios for achieving water reuse in nature/agriculture or industry.

overlap of membrane technologies in the steps. These additional value factors can balance the additional capital and operational costs [36]. Noting nutrient removal will be required after anaerobic treatment, to convert or recover the N and P fractions, as outlined in Figure 1.

The operation can also be streamlined with reduction in lower solid influent (post settling sewage) through preconcentration, where the solids are separated through intensification of settlement or floatation and sent to a lower-rate AD tank (Figure 1a) [41]. The solids-free

**Figure 2**




Schematic for sustainable *WWTP-of-the-future* with core mainstream anaerobic treatment and resource recovery platform. This figure highlights the adaptability that anaerobic system offers with varied 'treatment process flows' possible. Overall, starting with pretreatment recovery-based screening, moving through anaerobic removal of organic carbon and conversion to biogas with options for nutrient, energy, water and resource recovery. Crucially, this highlights the potential for the future and adding-value through the production of more valuable products, for example, VFAs, methanol and especially through the value addition to producing directly reuseable water.

liquid stream can be then treated anaerobically with a membrane at high HRTs (~4–6 hours) avoiding fouling, high dissolved methane, and suboptimal BOD:-S ratios. However, the first separation step requires a techno-economic viability and the BOD:S ratio should then be accounted for in the remaining liquid fraction.

## Designing the wastewater treatment plant of the future with an anaerobic core

To truly achieve net-zero carbon emissions and a fully circular wastewater treatment sector, severe changes must be considered for our future WWTPs. With this in mind, we outline here (Figure 2) a variety of options for various WWTPs with the current best available research and potential for wastewater treatment and resource recovery.

The wastewater should first undergo advanced screening, separating out any large solids (Figure 2). These solids contain both organic and inorganic components, which would be treated separately. The inorganic fraction of these solids could be sent for incineration, generating thermal energy, while the organic, cellulose-rich fractions would be digested into volatile fatty acids (VFAs) or refined into a recycled cellulose product (such as those commercialised by Cirtec®).

Moving next to the core biological step, the screened wastewater, free of large inorganic solids, would enter the mainstream, ambient-temperature anaerobic phase (Figure 2). Mainstream anaerobic bioreactor directly converts the carbon, BOD, to biogas with or without a membrane system depending on the requirement for recovery of resources.

In certain cases, the avoidance of high-volume low-load sewage could be possible through the predesign of black-water systems in decentralised new or developing areas, offering more direct efficiencies with anaerobic treatment of solids and isolation for resource recovery from other streams, namely, grey and storm waters [42,43].

Similarly, preconcentration (at primary settlement stage as mentioned above) of the organic through intensification of settlement or floatation combined with side-stream AD presents a promising alternative for utilising current assets (low-rate anaerobic digestors) [41].

From the anaerobic biological step, biogas is produced. However, methane solubilises at low temperatures in the effluents and without active removal will degas to the atmosphere, with losses of up to 80% of produced methane from a system [44,45]. Therefore, degassing step is essential for implementation, actively limiting atmospheric GHG emissions and enabling carbon-negative treatment. There are several methods that can be deployed. On nonmembrane systems, liquid degassing is possible via market-ready methane vacuum degassing, with an expected usage of 0.2 $kWh/m^3$ but overall recovery of up to 0.7 $kWh/m^3$ (Elovac Gmbh., unpublished, [46]). Further technologies such as air stripping [47] and contactors membrane removal are also well researched at full scale [48]. Biological oxidation is also feasible, while not yet at commercial scale, potential for linking methane oxidation with nitrogen removal has been researched [49,50].

While for AnMBR plants, degassing membrane technology offers particularly high recovery yields and efficiencies demonstrated in various studies [51,52].

Finally, following capture, the biogas should be utilised and offset fossil fuel usage. Dependent on the WWTP size, low biogas volume may present another challenge for its utilisation. When onsite use is unnecessary or infeasible, it is possible to convert or accumulate the biogas by (i) bottling or grid injection (at a larger facility) or (ii) methane oxidation and conversion to methanol.

As an alternative to biogas use, the production of other high-value products from biogas or direct from AD is recently undergoing significant research and development. Production of a wide range of VFA chemicals or even hydrogen [53,54] is currently achievable from concentrated wastewaters through removal or inhibition of methanogenesis. Such technologies could conceivably be adapted to fit into an anaerobic-centric model for municipal wastewater treatment (Figure 2), turning the entire process from resource utilising to high-value resource producing. However, to ensure efficiency, proof-of-concepts need to be piloted on diverse and dilute municipal wastewater streams.

Following mainstream anaerobic treatment, the effluent is BOD limited but nutrient rich. The removal of N can be achieved via direct partial nitrification-annamox with conversion to $N_2$ [49,55–57]. However, several other methods are available via phototrophic or algal biomass growth (commercially demonstrated by Arbib et al., 2017 [58]). Ammonium can be recovered through various developing technologies, such as stripping, membrane contactors, and struvite precipitation amongst others [51,59]. Recovery of P could additionally be achieved in a BOD-limited environment through precipitation in struvite, vivianite, or calcium phosphate recovery or adsorption [60]. While these technologies such as ion-exchange are being optimised in the field, as with post-CAS recovery of nutrients they yet to be accepted as standard practice. The low energy recovery efficiency and therefore techno-economic feasibility will follow driven by market demand in the expected shift from single-use nutrients.

Overall, this shift to anaerobically treated wastewater is a unique opportunity to recover the largest resource — water. To polish the treated wastewater for nonpotable reuse purposes, low-energy options should be evaluated and could include trickling filters, sand filters, reed beds, or polishing ponds (Figure 1). Further nature-based solutions [61] and agricultural (fertiirigation) [62] offer positive solutions that would fit well into this platform in certain scenarios.

However, for water reuse to potable water, tertiary treatment requirements such as advanced oxidation processes and adsorption through activated carbon, for example, should be considered. Utilising more membrane-based treatment trains is also possible to facilitate the recovery of additional resources from the effluent (e.g. ammonia) while controlling GHG emissions and potentially CECs [63]. Initial studies show that incorporating anaerobic treatment technologies to reuse trains could result in higher quality treated potable water: anaerobic treatment could be more effective at removing select classes of emerging contaminants [52] compared to aerobic treatment and at controlling disinfection by-product precursors, which are priority pollutants in reuse trains [64]. The fate of additional contaminants in anaerobic-centric approaches requires significant investigation, with current investigations outside of scope on temperature, scale, or applicability [65–67].

Converting traditional treatment into a mainstream anaerobic-centric treatment would transform the entire wastewater treatment process from a resource-utilising, linear, disposal-based model to a true resource-producing, circular water reuse platform. However, full implementation of such mainstream anaerobic treatment process flows is still in its infancy (especially in temperate climates), and research-based leadership is required by utilities. Further development is clearly required, especially in terms of process integration, but also in terms of degassing, nutrient removal, water reuse, all in a low-energy manner and, finally, not least, societal and professional acceptance (Table 1). Advancements in these areas would have the largest positive impact on the field, propelling wastewater treatment and the plants of the future towards true sustainability and circularity.

**Table 1**

**Key knowledge gaps and research questions for achieving Anaerobic Core of WWTP-of-the-Future.**

| Key question | Process section | Sector | Importance (1, most – 5, least) |
|---|---|---|---|
| Choosing the correct inoculum biomass (e.g.. activity, diverity and substrate specificity). | Microbiology | Academia | 1 |
| Qualifying the requirement for degassing; Quantifying the level of supersaturation of methane in effluent across temperature gradients: $<20°C$, $<15°C$, $<12°C$, $<8°C$ | Degassing | Academia and industry | 2 |
| How reliable is partial denitrification/anammox when N must be removed, including potential $N_2O$ emissions quantification? | Nutrient removal | Academia and industry | 3 |
| What BOD is required to upkeep current CAS systems successfully removing N/ammonia? Allowing for partial mainstream anaerobic treatment as a step-wise improvement | Current system integration | Industry | 2 |
| What cost and $CO_2$ emissions are involved with various upgrades to WWTPs to implement non-CAS nutrient removal? | Nutrient removal | Industry | 5 |
| Outline the options available to municipalities to begin the more direct water reuse and its value per $m^3$. | Water reuse | Industry and policy | 4 |
| What is the fate of emerging contaminants in AD systems? | Emerging contaminants | Academia and industry | 3 |
| Clear matrix for membrane options for each stage and their cost of operation, including when utilised together for each stage or resource and its recovery. | Membrane – resource recovery | Industry | 2 |

## Conclusions

Current standard WWTPs and their core aerobic technologies are failing to take on the large paradigm shift required to meet the climate crisis in the form of the global circular economy and net-zero goals.

- Aerobic treatment is a successful but linear technology that limits carbon neutrality in wastewater treatment.
- Anaerobic microbiology can underpin the municipal WWTP of the future. Recent advances and successful scaled demonstrations have validated the efficacy of anaerobic treatment as a primary carbon removal step for the treatment of municipal wastewater in temperate regions.
- The utilisation of anaerobic treatment as the core of the WWTP would transform the pathways to resource recovery (C, N, P, and water):
  - Inherent sludge reductions (up to 95%) and energy savings (~50%)
  - Flexibility for additional carbon-free side-stream applications for the recovery of (more) energy, nutrients, and water.
- Water reuse in nonpotable and potable uses would be possible even with the presence of emerging contaminants following further confirmational research; however, its value should be defined to allow for sufficient investment in the WWTP.
- Separating the requirement(s) for water treatment with nutrient recovery and final water reuse is key to the decision of which technologies should be utilised. All can be achieved with various anaerobic technologies.

The change from aerobic microbiology to anaerobic microbiology in wastewater treatment is the foundation required to implement the next generation for water. Given water is our keystone resource for humanity and sewage is ubiquitous to every person and community globally; this change is unique in its ability to be impactful in humanity's fight for limiting our climate crisis.

## Author Contributions

The foundational writing of this manuscript was led by BCH, AT, CK, DH, and VOF. Following this, the manuscript we find here was drafted equally through edits additions and adaptations by all authors. It was then finalised by BCH, AT, A. Szcuka, AR, and EP. Figures were originally drafted by DH, finalised by BCH. BCH and VOF are the co-corresponding authors.

All authors approve the manuscript and agree for accountability of the work therein.

## Data Availability

No data were used for the research described in the article.

## Declaration of Competing Interest

The authors declare no competing interests.

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