Transitioning Wastewater Treatment Plants toward Circular Economy and Energy Sustainability

Umesh Ghimire, Gideon Sarpong, and Veera Gnaneswar Gude*

ABSTRACT: Aging infrastructure, increasing environmental regulations, and receiving water environment issues stem the need for advanced wastewater treatment processes across the world. Advanced wastewater treatment systems treat wastewater beyond organic carbon removal and aim to remove nutrients and recover valuable products. While the removal of major nutrients (carbon, nitrogen, and phosphorus) is essential for environmental protection, this can only be achieved through energy-, chemical-, and cost-intensive processes in the industry today, which is an unsustainable trend, considering the global population growth and rapid urbanization. Two major routes for developing more sustainable and circular-economy-based wastewater treatment systems would be to (a) innovate and integrate energy- and resource-efficient anaerobic wastewater treatment systems and (b) enhance carbon capture to be diverted to energy recovery schemes. This Mini-Review provides a critical evaluation and perspective of two potential process routes that enable this transition. These process routes include a bioelectrochemical energy recovery scheme and codigestion of organic sludge for biogas generation in anaerobic digesters. From the analysis, it is imperative that integrating both concepts may even result in more energy- and resource-efficient wastewater treatment systems.

INTRODUCTION

To protect the quality of receiving water bodies and the environment, carbonaceous and nutrient (nitrogen and phosphorus – N and P) compounds must be efficiently removed from wastewater sources. Most wastewater treatment plants remove organic matter only through energy-inefficient configurations. Conventional wastewater treatment systems for nitrogen removal rely on excess chemicals and energy to create aerobic conditions for biological nitrification and use organic carbon to remove nitrate by biological denitrification. Instead, the design of sustainable wastewater treatment systems must focus on environmental protection and minimize energy and resource consumption. In this context, novel wastewater treatment systems that produce net energy while removing nutrients are actively sought. Anaerobic wastewater treatment is a proven and beneficial route from energy and environmental perspectives. Similarly, an alternative approach for baseline nitrification-denitrification process is to use anaerobic ammonium-oxidizing (anammox) bacteria, which reduces energy and chemical costs. Under anaerobic conditions, bioelectrochemical systems provide efficient wastewater treatment while generating clean electricity directly from organic substrates. Integrating these technologies is essential to further enhance the potential for energy recovery and for developing sustainable wastewater treatment systems.

ENERGY CONSUMPTION IN WASTEWATER TREATMENT

Approximately 80% of the municipal wastewater is treated in developed countries using the aerobic process known as activated sludge process, for the removal of organic carbon and nitrogen compounds. Aeration accounts for majority (>60%) of the energy required for the treatment, which depends on wastewater characteristics, treatment scheme, and plant capacity, the average electrical energy intensity being 0.13–0.79 kWh per m³ wastewater treated. Energy sustainability in wastewater treatment plants is a crucial step in moving forward with advanced treatment processes. About 5% of the total energy is used to treat and supply drinking water and treat wastewater generated at the national level (in the U.S.). Wastewater treatment plants alone can occupy 25–40% of the local electricity budget in the case of small communities, which is considered a significant energy and environmental burden for these communities. Wastewater treatment energy consumption also depends on process configurations and geographical variability. For instance, the average energy consumption for activated sludge treatment plants in Europe is between 0.15 and 0.7 kWh/m³. The average specific energy consumption values in some developed countries such as Germany, Italy, The Netherlands, United Kingdom, and the United States are 0.67, 0.55, 0.47, 0.64, and 0.45 kWh/m³, respectively, which is affected by various aforementioned factors. It should be noted that anaerobic treatment processes avoid the need for aeration and may reduce the specific energy consumption for overall treatment.

Received: November 30, 2020
Accepted: April 19, 2021
Published: April 27, 2021

© 2021 The Authors. Published by American Chemical Society

https://doi.org/10.1021/acsomega.0c05827
In addition, the potential for biogas generation can be higher than the energy required for heating the digesters.

Energy requirements for wastewater treatment vary based on the process configuration, the treatment goals, and effluent standards. Most commonly, the energy consumption is less than 0.5 kW h/m³ for processes not including nutrient removal. Water reuse plants include advanced treatment processes for removing nutrients, pathogens, and other emerging contaminants often employ membrane filtration and gradual activated carbon filtration processes. These processes are energy-intensive with a specific energy consumption between 0.5 and 2.0 kWh/m³. Aeration equipment are the major energy consumers in activated sludge processes. Other significant contributing factors are mixing and pumping. Low-energy-footprint technologies such as trickling filters and aerated lagoons require 0.18–0.42 kWh/m³ and 0.09–0.29 kWh/m³.\textsuperscript{11}

### ENERGY RECOVERY POTENTIAL IN WASTEWATER TREATMENT

Wastewater contains significant quantities of chemical energy which can be converted to electrical energy or heat. For example, primary sludge contains approximately 66% of the energy entering the treatment plant, with the rest entering secondary treatment.\textsuperscript{12} A much higher value for energy content with an approach that minimizes the loss of volatiles was also reported.\textsuperscript{13} It was also reported that the energy available in a typical municipal wastewater exceeds the energy required for treatment by a factor of 10.\textsuperscript{12} It should be noted that not all of the available energy in wastewater can be harvested in a beneficial form.\textsuperscript{12,13} However, an understanding of the available energy in the wastewater is a critical step toward developing energy and resource recovery schemes in wastewater treatment plants.

An anaerobic digestion process generates biogas (CH\textsubscript{4}) which can be used compensate a portion (25−50%) of the energy requirements in the activated sludge process, and other plant modifications may also further reduce energy needs considerably.\textsuperscript{14} However, if more of the energy contained in the wastewater were captured for use and even less were used for wastewater treatment, then the wastewater treatment plants may become net energy producers rather than consumers. An energy balance comparison between the conventional activated sludge (CAS) treatment and anaerobic digestion process shows that the CAS process requires 25 kW h of electrical energy per capita per year, whereas the new design with anaerobic digestion produced a net energy of 5 kW h of electrical energy. This means that by not implementing novel treatment units and processes about a 30 kW h per capita per year equivalent electrical energy losses can be realized.\textsuperscript{14}

**Circular Economy through Codigestion.** Energy recovery potential in a wastewater treatment plant depends on various factors such as wastewater characteristics (low strength vs high strength in terms of COD), process operating scheme (biological treatment process), plant capacity, and energy recovery scheme.\textsuperscript{15−17} Wastewater treatment plants can adopt circular economy principles—a concept revolving around keeping materials and products in the economy as long as possible by promoting recycle and reuse—both at small- and large-scale applications. Many wastewater treatment plants are currently exploiting the additional digestion capacity of existing anaerobic digesters to process external high strength organic wastes for better utilization of the plant footprint and for generating additional revenues. By processing external organic wastes such as FOG (fats, oil and grease), food waste, and agricultural wastes, wastewater treatment plants can transform the waste into high-value beneficial products such as methane and biosolids. Revenues can be generated by accepting these wastes from producers (a tipping fee can be implemented to receive the waste) and with additional income from the biogas generation. Techno-economic feasibility of codigestion of plants has been proven to be quite attractive. However, the cost−benefit scenario mainly depends on factors such as affordable tipping fees by organic waste producers, anaerobic digester capital costs, organic waste characteristics, electricity costs, and biosolids’ residual management costs. The most feasible codigestion facility would receive organic waste with high volatile solids, have high electricity rates to get the most value of the biogas (assuming a combined heat and power - CHP unit), and have lower residual management costs or have additional revenue generated from residual biosolids, if possible.

Figure 1 shows a summary of energy recovery potentials in U.S. wastewater treatment plants.\textsuperscript{7} It is clear that the energy recovery potential of a wastewater treatment plant does not simply depend on the plant capacity. These plants codigest different forms of organic wastes such as fats, oil and grease, high strength wastes, food waste, and primary and secondary sludge from the wastewater treatment plant itself. A variety of energy recovery schemes are also in place. For example, small capacity plants incorporate microturbine or steam turbines (<400 kW) and fuel cells (<250 kW), while large-capacity plants use boilers, gas turbines, and internal combustion engines (up to 5 MW).\textsuperscript{18}

### THE CHALLENGE OF CARBON AND NITROGEN REMOVAL FROM WASTEWATER

Aeration and pumping are the two major energy consumers within the CAS process as mentioned earlier; combined, they account for 70−80% of the total energy consumption.\textsuperscript{3} On the other hand, biological nitrogen removal with nitrification and denitrification approach is a resource-demanding and high-energy-consuming process.\textsuperscript{4,19} These processes require aeration and additional organic carbon, respectively, together resulting in energy and chemical consumption. An additional environmental impact is due to high biomass production and
greenhouse gas (CO₂, N₂O, etc.) emissions. However, anammox bacteria convert ammonium and nitrite directly to dinitrogen gas (N₂) under anoxic conditions. Anammox-based nitrogen removal occurs with a significant reduction of energy consumption (60%) and greenhouse gas emissions, GHG (90%) compared to other biological nitrogen removal processes. In partial nitritation-anammox wastewater treatment plants, ammonium-oxidizing bacteria (AOB) convert about half of the supplied ammonium to nitrite under O₂ limitation, and in turn, nitrite, together with the remaining ammonium, is converted to N₂ by anammox bacteria. Nitritation-anammox systems are currently applied in the side-stream treatment of high-strength wastewaters, such as digester effluents and anaerobically treated industrial effluents. Mainstream utilization of this process is not yet possible because of many unidentified constraints in its feasibility.

In the above context, there are two main opportunities for developing potentially energy-positive nutrient removal processes. These can be based on microbial electrochemical systems and microalgae-mediated wastewater treatment systems. Conventional biological nutrient removal process consumes between 0.412 and 0.780 kWh/m³, whereas a simultaneous nitritation and autotrophic denitrification process coupled with a microbial fuel cell has shown many benefits (aeration savings, electricity generation, and carbon savings), resulting in a net energy production of 0.0066−0.007 kWh/m³. Codigestion combined with a microalgae-based nutrient removal process can enhance the biogas production by 30% albeit with sludge pretreatment.

**RESOURCE-EFFICIENT WASTEWATER TREATMENT SCHEMES**

Resource-efficient (less chemical and energy consumption) nutrient removal is an ongoing challenge. Sustainable wastewater treatment systems should be designed to maximize energy and resource (nutrient and water) recovery. Water is the major and the most valuable resource that can be recovered from these operations. While current aerobic processes for carbon and nitrogen removal are energy-intensive, energy recovery in wastewater treatment can be achieved by concentrating and converting organic compounds to CH₄ in an anaerobic digester. The remaining ammonia-containing wastewater will then undergo a nitritation-anammox process for nitrogen removal. Biogas production through this approach is attractive, but it is only an intermediate product requiring separation and refinement prior to use. Direct electricity production from wastewater is an attractive option to eliminate the need for process-intensive separation. Wastewater facilities with large capacities (>50 MGD) may have a maximum energy recovery efficiency of up to 40% (based on methane generation). The hydrogen-based industry has not been established yet because of several technical and practical drawbacks to consider before the biophyrogen production route can be a feasible alternative. Microbial systems having the potential to convert chemical energy (in the form of organic compounds) into electrical energy are known as bioelectrochemical systems, and they show potential for higher energy recovery up to 65%.

To develop resource-efficient (energy self-sufficient) wastewater treatment systems, two major routes can be considered: (i) enhance carbon capture to be diverted to energy recovery schemes and (ii) innovate and integrate energy- and resource-efficient anaerobic wastewater treatment schemes or systems. More details of these two routes are presented in the following sections.

**Enhance Carbon Capture for Energy Recovery via Anaerobic Digestion.** Enhancing carbon removal by capturing sludge from the primary and secondary treatment units will increase biogas production potential allowing for higher energy recovery. For instance, the Oregon County Sanitation District enhanced its primary treatment process, which increased its biogas production by 18%. Alternative feedstock such as food waste (FW), fats, oils and grease, and other organic wastes have been adopted by many utilities to increase biogas production. The energy content in organic wastes such as FOG suggests their use as feedstock for biogas production. It is reported that FOG not only increases biogas production but also stabilizes digester operation.

**Integrate Anaerobic Treatment and Bioelectrochemical Systems (BES).** Microbial fuel cells (MFCs) are one form of BES in which organic substrates (similar to those in wastewater) are biodegraded in the anodic compartment involving the release of electrons which pass through an external load as electric current. The electric current will then combine with a cathode electron acceptor through electrocatalytic or biocatalytic reduction reactions. Municipal wastewater contains a multitude of organic compounds that can fuel MFCs, and the amount of power generated by MFCs in the wastewater treatment process can significantly reduce or even completely eliminate the electricity needs for aeration in conventional treatment processes. MFCs can remove both carbon and nutrient compounds simultaneously.

The anammox process was first observed to occur in ocean sediments and was attributed to releasing a significant amount of N₂ into the environment. Thus, anammox bioelectrochemical systems (ABCs, Anammox Bioelectrochemical systems—anammox biofilm or granules used as biocatalyst or biocathode for nitrogen removal in bioelectrochemical systems, especially as biocathode in microbial desalination cells) may solve two primary issues: their resistance to a variety of high concentrations of inorganic compounds will ensure a sustained process operation in carbon and nitrogen removal, and the reductive and oxidative processes by these bacteria that involve nitrogen transformation consisting of higher electrochemical potential may generate a higher electrical voltage (this is a current limitation of MFCs since the abiotic cathodes need to be replenished to charge their chemical/electric potential and they do not accommodate nitrogen removal).

A mass balance of such process configuration integrating anammox nitrogen removal in a bioelectrochemical system is shown in Figure 2. The primary assumption of this mass balance is that in domestic wastewaters, COD and nitrogen (quantities) approaching the treatment system would be 110 g-COD and 10 g-nitrogen per person per day, respectively. Similarly, COD and nitrogen leaving the wastewater treatment system in the effluent and digested sludge would be 5 g-COD and 1.5 g-nitrogen per person per day, respectively. It can be noted that about 20% (23 g-COD) of influent COD can be recovered in the form of electricity in addition to the 30 g COD in the form of biogas in the anaerobic digester.

**EVALUATION OF RESOURCE-EFFICIENT PROCESS SCHEMES**

On the basis of the above two major routes, the following treatment schemes can be proposed (Figures 2—4). Conventional wastewater treatment scheme (primary treatment
followed by a biological treatment unit and a secondary clarifier including anaerobic digestion of primary and secondary sludge with anammox denitrification can be considered as a base case. The other proposed schemes are as follows.

1. Conventional wastewater treatment scheme (S1 - base case) with anaerobic digestion where the primary settling tank (with 0.5−1 h of hydraulic retention time) collects 20−25% organic matter in the form of sludge entering the plant. This scheme includes a denitrification step. This sludge then combines with the secondary sludge to be routed for anaerobic digestion (see Figure 3). More details can be found in Siegrist et al.43

2. Scheme 2 (S2) considers an increased settling time (with 2−3 h of hydraulic retention time) in the primary settling tank to enhance organic matter collection thereby methane production in the anaerobic digester (see Figure 3).

3. Scheme 3 (S3) considers an integrated process including anaerobic treatment and anammox treatment processes to minimize aeration energy consumption for both organic carbon and nitrogen removal and increase sludge digestion to enhance methane production.21,44,45

4. Scheme 4 (S4) considers a bioelectrochemical system where the organic matter is converted to an electron flow to be harvested as electricity followed by nitrogen removal in a simultaneous nitrification and anammox denitrification (SNAD) process (see Figure 2).42

5. Scheme 5 (S5) includes enhanced primary settling techniques (in addition to longer hydraulic retention time, HRT) such as micro or disk filters to increase carbon capture to be processed in the anaerobic digester.16,17,46,47 External organic feedstock such as fat, oil, and grease and high strength organic waste sludge from food, dairy, and agricultural industries are also fed to the digester to enhance biogas production.

6. Scheme 6 (S6) considers the integration of biological carbon and nitrogen removal in a bioelectrochemical system using heterotrophic and mixotrophic (hetero and autotrophic) biofilms for bioelectricity generation.48,49 This configuration (ABC) facilitates simultaneous carbon and nitrogen removal by using an anammox biocathode process. Both S5 and S6 configurations involve enhanced carbon capture in primary treatment so that lower amounts of carbon will require further removal by biological processes (see Figure 2).

Mass Balance. It is assumed that about 1 kWh/m³ of energy is required to treat the municipal wastewater with a COD concentration of 250−300 mg/L.50 In this study, the wastewater COD concentration is estimated at 275 mg/L. For a wastewater quantity of 400 L per day per person, the amount of COD that is present in the wastewater is 110 g per person per day. Therefore, the mass balance for scenario 1 and 2 for COD and nitrogen removal is as follows. More details can be found in Siegrist et al.43 Initially, the nitritation/anammox process was operated with continuous aeration at oxygen concentration, 0.5 g O₂m⁻³ in a 400-L reactor. After six months of operation, the process was up-scaled to an 8 m³ SBR (sequential batch reactor) pilot with a 1.2 d HRT.

Energy Analysis. Scenarios 1 and 2 are based on anammox denitrification with a separate nitrogen removal step as shown in Figure 3. The anammox denitrification process is a short-cut process which reduces the external carbon and aeration demands significantly. This process does not follow the typical...
nitrification (nitritation and nitratation) followed by a denitrification route. Instead, the anammox bacteria are able to directly utilize ammonium and nitrite to release nitrogen. Anammox bacteria use CO₂ as their carbon source for growth and hence do not require organic carbon. The nitrite required for their growth may be provided by aerobic ammonium-oxidizing bacteria or archaea. The anammox and nitrification reactions and combined reaction are shown below.21

\[
\begin{align*}
\text{NH}_4^+ + \text{NO}_2^- & \rightarrow \text{N}_2 + 2\text{H}_2\text{O} \\
\text{NH}_3^+ + 1.5\text{O}_2 & \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O} \\
2\text{NH}_4^+ + 1.5\text{O}_2 & \rightarrow \text{N}_2 + 2\text{H}^+ + 3\text{H}_2\text{O}
\end{align*}
\]

with 0.5–1 h settling time in the primary settling unit, the sludge capture efficiency would be between 20 and 25%. A conservative estimation of 1 kWh/kg COD removal was used in calculations. This assumption also supports the energy consumption values reported by Siegrist et al.43 Similarly, based on several pilot-scale studies for DEMON (partial nitritation and subsequent anaerobic oxidation of ammonia) and SBR anammox processes, the energy demand for nitrogen removal is estimated as 1 kWh/1 kg N in this process.51 The energy consumption for mixing and pumping in conventional wastewater treatment plants varies between 0.012 and 0.033 kWh/m³.11 Therefore, each gram of COD contains 13.9 kJ of energy.52 Therefore, the following equation provides the energy generated from the sludge digestion for methane generation.

\[
E_G = \frac{\text{COD}_{\text{m}} \times \text{COD}}{3600 \text{ kJ/kWh} \times \text{M-P}}
\]

where \(E_G\) = electricity generated; \(\text{COD}_{\text{m}}\) = amount of COD converted to methane, \(\text{COD}\) = energy content of COD, \(\text{M-P}\) = methane to power conversion efficiency (33%).

For Scenario 2, the settling time in the primary clarifier is increased to 2 h to enhance carbon capture through sludge separation. The sludge capture efficiency was increased to 30–48% in this configuration resulting in higher flow of sludge directly sent to the anaerobic digester, thus reducing the aeration needs in the downstream process (i.e., activated sludge process). The rest of the analysis is similar to Scenario 1.

Scenario 3 includes mainstream anammox process that enhances nitrogen removal and COD load on the activated sludge process. Aeration requirements are significantly lower than the other biological processes presented in Scenarios 1 and 2.

Scenario 4 includes a microbial fuel cell system (a bioelectrochemical system) followed by a simultaneous nitritation and autotrophic denitrification (SNAD) step. It is assumed that about 20 g of COD (30% of the influent) is converted to bioelectricity. Thirty grams of COD is removed as CO₂.

More details about scenarios 1–4 can be found in Siegrist et al. (Scenarios 1 and 2);43 Kartal et al. (Scenario 3);21 and Ali and Okabe (Scenario 4).42

Scenario 5 is based on a conventional biological treatment system with low, medium, and high influent COD strengths assumed as 390, 720, and 1230 mg COD/L, respectively.16,17 In addition to the enhanced carbon capture in the primary treatment unit, this option considers energy saving alternatives and the addition of external highly biodegradable organic feedstock including a CHP (combined heat and power) system.

Figure 4. Outline of potential resource-efficient wastewater treatment schemes with energy profiles (Wh/person-day). C = carbon capture; E = external organic feedstock; AS = Activated Sludge; AD = anaerobic digester; AN = anaerobic treatment; AMX = anammox denitrification; MFC = microbial fuel cell; SNAD = Simultaneous nitritation and anammox denitrification; ABC = anammox bioelectrochemical system; OCR: energy loss in organic carbon removal; A-N: aeration energy for nitrogen removal; P/M: energy for pumping and mixing.

https://doi.org/10.1021/acsomega.0c05827
ACS Omega 2021, 6, 11794–11803
Scenario 6 is based on the anerobic treatment of wastewater for COD removal in the anode compartment and partial nitritation/anammox based nitrogen removal in the cathode. Details of this process were presented in our previous study. A COD concentration of 500 mg/L and ammonium and nitrate ion concentrations of 70 mg/L were used in that study with a detention time of 72 h. Finally, in all cases, the net energy ratio is calculated as the ratio of the energy produced to the amount of energy consumed in the process.

**Energy Sustainability.** The energy consumption and production potential details are shown in Figure 4 and Figure 5. It can be noted that the aerobic carbon removal process (AS in S1, S2, and S5) involves significant energy consumption (Wh/person-day). While the ability to recover energy through biogas production exists, the net energy recovery potential is below the level of energy self-sufficiency. Scheme 3 (S3) overturns this situation by incorporating anaerobic treatment in lieu of an activated sludge process and by enhancing the AD process. Similarly, Scheme 4 (S4), by replacing the activated sludge process with an integrated bioelectrochemical system further enhances energy recovery potential. It should be noted that the organic carbon removal process in this configuration actually contributes to energy generation. Further, this energy is produced directly from waste sources without the need for refinement indicating a higher value when compared with methane produced from AD in other configurations, which need further cleaning and conversion. Scheme 6 (S6) is a modified resource-efficient treatment route similar to S4. In this configuration, the bioelectrochemical removal of carbonaceous and nitrogenous compounds by electroactive biofilms contributes to net energy generation while still allowing for biogas generation through AD. The energy consumption rates in S1, S2, S3, S4, and S6 are -82, -72, -46, -31, and -10 (Wh/person-day), respectively, while the energy generation potentials are 38, 70, 78, and 58 (Wh/person-day) respectively. The net energy recovery ratios for these schemes are 0.46, 0.71, 1.52, 1.87, and 5.8, respectively. The corresponding self-sufficiency levels are then expressed as 46%, 71%, 152%, 187%, and 580%, respectively. In S5 and S6, the question marks (?) in Figure 4 refer to the potential for further improvements. For example, the carbon capture (sludge removal) can be improved by up to 30% to reach a total of 60% solids removal in the primary settling process, which in turn, will reduce the aeration, chemical addition, and pumping requirements in the downstream process. As a result, S5 shows significant potential for increasing biogas production and for reducing energy consumption, the two essential steps for net energy ratio enhancement. Similarly, S6 eliminates the need for additional steps and integrates both carbon and nitrogen removal processes in a single bioelectrochemical system to exploit the electrochemical potentials. The net energy ratio for S6 is based on laboratory-scale experimental results presented in our previous study. A comparison of Scenario 6 with Scenario 3 and one other study is shown in Table 1. Overall, an analysis based on Figure 4 and Figure 5 shows that both energy consumption and energy recovery should be optimized to gain higher net energy ratios.

As mentioned before, Scheme 5 includes external organic feedstock addition to the anaerobic digestion to enhance biogas production to be converted to electricity and heat through CHP units. Here, the selection and design optimization of energy recovery schemes are very important. For example, the CHP scheme is widely recognized as a reliable method to recover energy in the forms of both electricity and heat from various sources. For wastewater treatment plant applications, it is important to select the correct size and number of CHP units for energy recovery from AD biogas. Figure 6 shows an energy return (net energy ratio) analysis for a 20-MGD wastewater treatment plant that is receiving a 5-tpd (Tons per day) of FOG. In this analysis, low-, medium-, and high-strength wastewaters as well as different CHP (internal combustion engine) engine capacities (100–800 kW) with and without codigestion options are considered. More details can be found elsewhere.

The challenge is to determine the optimum size and number of CHP units that will result in low gas flaring (or waste) and high energy recovery from AD biogas. It is evident that energy self-sufficiency is not possible for low- and medium-strength wastewater plants that do not include codigestion. 100, 200,

---

**Table 1. Comparison of Scenario 6 with Other Anammox Nitritation Process**

| process                     | reactor volume (L) | HRT (hrs) | COD removal efficiency (%) | TN removal efficiency (%) | energy consumption (kWh/m³) | energy production (kWh/m³) | reference |
|-----------------------------|--------------------|-----------|----------------------------|--------------------------|----------------------------|---------------------------|-----------|
| ABC process (S6)            | 0.06               | 72        | 72.1                       | 70.0                     | 0.0221                     | 0.049                     | 49        |
| nitritation/anammox MBR     | 4                  | 12        | 96                         | 81.0                     | 0.09                       | none                      | 53        |
| nitritation/anammox process (S3) | 400              | 2         | 48                         | 15                       | 0.021                      | none                      | 43        |
Figure 6. CHP unit optimization analysis for different wastewater strengths with and without codigestion based on energy return values for a 20-MGD plant capacity with 30% primary treatment efficiency, 30 days SRT for AD, and an AD temperature of 30 °C and 5-tpd FOG addition.59

and 600 kW CHP engines are preferable for high-strength wastewater plants without codigestion. Similarly, it is a challenge for a low-strength wastewater plant to reach energy self-sufficiency even with codigestion. Both 100 and 200 kW CHP engines are preferred for medium-strength wastewater treatment plants with codigestion to achieve energy self-sufficiency. Finally, 100, 600, and 800 kW CHP engines are preferable for high-strength wastewater plants with codigestion. Note that the results will vary for the above scenario with plant capacity and primary setting process efficiency, and these can be found elsewhere.16,17

**DISCUSSION**

There are many possible solutions for accomplishing energy self-sufficiency or energy-positive status in wastewater treatment plants. Here, we compared six different process configurations and identified two key processes that may enable this transition more efficiently. While the proposed scenarios (S5 and S6) are quite attractive from circular economy and energy sustainability perspectives, many barriers and challenges need addressing for their practical feasibility and wide application.

Regarding S5, co-digestion method has shown promising potential because the addition of FOG or other organic wastes for codigestion has a positive effect on the digestion process with higher methane yields and stable operations. Biogas production due to FOG codigestion could also increase from 15 to 30%, which is a significant contribution to electricity and heat recovery.16 C/N ratio, organic loading rate, pH, temperature, HRT, and pretreatment of organic substrates are all critical factors for the success of the codigestion process.35,56 While there are several benefits of integrating codigestion of mixed waste for energy production, there are a few challenges that are worth mentioning. One of the biggest challenges is the generation of sludge caused by digesting additional waste such as FOG with inconsistent characteristics and their land application. Significantly higher nutrient concentrations present in supplemental feedstock also pose permit-specific issues. Material handling infrastructure may face corrosion because of acidic streams. Further, AD effluents containing nutrient residues encourage proliferation of unwanted microorganisms during the CAS process. Overall, the economic, energy, and environmental benefits outweigh the aforementioned issues. FOG addition increases biogas production by 2-fold. Upfront or upstream removal of FOG prior to the activated sludge unit has a significant impact on the efficiency conservation and efficiency of the downstream process. Moreover, codigestion of FOG in anaerobic digesters would be more cost-effective and environmentally friendly.57

Food and agricultural wastes also can be valorized using anaerobic digester technology.58 An estimated 1.6 billion tons of food waste is available worldwide,56 which can be converted to valuable energy products (biofuels such as biodiesel, bioethanol, and biooil or biocrude) through various thermochemical and biochemical processes. However, AD is a preferred and most feasible method for waste valorization especially when combined with CHP units.59

Regarding S6, the long-term performance of the anammox process both in laboratory and pilot/field scale studies has shown evidence of slow nitrogen removal rates. The reasons behind the poor performance are still not well understood, although it is sometimes attributed to the accumulation of dissolved oxygen content over time. The long-term performance and process feasibility for ABCs are still unknown. There are many process parameters that require deeper investigation and optimization. Understanding the evolution and maintenance of anammox biofilms or granules under bioelectrochemical system configuration is important for improving the stability of this process. In the ABCs’ process, the aerobic ammonium-oxidizing bacteria (AOB) play a very important role in the reduction of ammonium. The main role of AOB in the ABCs’ process is to convert approximately half of the ammonium to nitrite under partial oxygen condition, and in turn, anammox bacteria convert nitrite, together with the remaining ammonium, into nitrogen gas. Therefore, the development of the strategy for maintaining the balance between AOB and AnAOB (anaerobic ammonia-oxidizing bacteria) in the biofilm of single-stage ABCs and simultaneously inhibiting the nitrite-oxidizing bacteria (NOB) would lead the ABCs toward higher nitrogen removal efficiency.

Development and implementation of three-dimensional conducting electrodes in ABCs can assist anammox granules/biofilm in easily attaching in the conducting medium, reducing electrical resistance between anammox bacteria and electrode increasing energy generation.

The partial aeration step used in the ABC process is still an energy-consuming process. A complete replacement of mechanical aeration system with biological oxygen-producing microorganisms would make ABCs more energy-positive. In this case, it would be interesting to consider the integration of anammox and microalgae polishing configurations. The oxygen produced by microalgae during the day time would provide enough dissolved oxygen for the partial conversion of ammonium to nitrite (partial nitritation process), and during the night time, microalgae will consume the dissolved oxygen to create an anoxic condition, which will be more favorable for anammox bacteria to remove the remaining portion of ammonium and combine with nitrite to form nitrogen gas.
CONCLUDING REMARKS
The need for developing resource-efficient wastewater treatment systems can never be overstressed considering the critical influence and role of treated effluents on the receiving environment. An evaluation and comparison of five different alternatives with a conventional treatment scheme, all including an anaerobic digestion step for biogas generation, shows that wastewater treatment plants can achieve energy self-sufficiency by enhancing carbon capture, by accepting external organic feedstock for energy recovery, and by implementing anaerobic bioelectrochemical treatment for electricity generation. All these steps taken together can help wastewater treatment plants march toward circular economy and energy sustainability, pending significant scientific and process related challenges to be overcome in near future.

AUTHOR INFORMATION

Corresponding Author
Veera Gnaneswar Gude — Richard A Rula School of Civil and Environmental Engineering, Mississippi State University, Mississippi State, Mississippi 39762, United States; orcid.org/0000-0002-0461-6510; Phone: 1-662-325-0345; Email: gude@cee.msstate.edu

Authors
Umesh Ghimire — Richard A Rula School of Civil and Environmental Engineering, Mississippi State University, Mississippi State, Mississippi 39762, United States
Gideon Sarpong — Richard A Rula School of Civil and Environmental Engineering, Mississippi State University, Mississippi State, Mississippi 39762, United States

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c05827

Funding
This research was supported by the United States National Science Foundation (NSF) under the grants EAGER 1632019 and REU-INFEWS 1659830.

Notes
The authors declare no competing financial interest.

Biographies

Umesh Ghimire received his B.S degree in Agricultural Engineering from Tribhuvan University Nepal in 2014. After that, he completed his master’s degree in Biological Environmental Engineering, Kangwon National University, South Korea in 2017. Currently, he has defended his Ph.D. Dissertation in the Department of Civil and Environmental Engineering, Mississippi State University, United States. His research focused on developing sustainable and energy-efficient technologies for wastewater treatment and energy production. More precisely, his work focuses on developing an efficient bioelectrochemical nitritation anammox process in microbial desalination cells to treat wastewater simultaneously producing electricity. More info at https://orcid.org/0000-0001-8918-2469.

Dr. Gideon Sarpong is currently the Environmental and Sustainability Manager for Nucor Steel LLC. He earned his B.Sc., Geomatics Engineering from Kwame Nkrumah University of Science and Technology in Ghana in 2007. He later obtained his Master’s degree in Civil and Environmental Engineering at New Mexico Institute of Mining and Technology in 2010. After working in the industry for almost 10 years, he obtained his Ph.D. in Civil Engineering from Mississippi State University in 2020. Dr. Sarpong is a licensed Professional Engineer in California, United States.

Dr. Veera Gnaneswar Gude is Kelly Gene Cook, Sr. Endowed Chair and Associate Professor of Environmental Engineering at Mississippi State University. He received Ph.D. in Environmental Engineering from New Mexico State University under the direction of Prof. Nagamany Nirmalakhandan and was a research associate with Prof. Shuguang Deng while at New Mexico State University. His research interests cover desalination, biofuel synthesis, and sustainable communities/energy systems topics, sponsored by NSF, USEPA, USGS, USDA, and other research agencies. He published over 100 research articles and seven books. He is a key member of several editorial and scientific advisory boards and professional societies.

ACKNOWLEDGMENTS
Dr. Gude acknowledges the support received from the Kelly Gene Cook, Sr. Endowed Chair in the Richard A. Rula School of Civil and Environmental Engineering at Mississippi State University. Umesh Ghimire was supported by the Kelly Gene Cook, Sr. Endowed Chair Fellowship. He also acknowledges
the James Franklin Brownlee Scholarship from the Bagley College of Engineering at Mississippi State University.

**REFERENCES**

(1) Davis, M. L.; Cornwell, D. A. *Introduction to Environmental Engineering*, 4th ed.; McGraw-Hill: New York, 2000.

(2) Wang, L.; Ben, W.; Li, Y.; Liu, C.; Qiang, Z. Behavior of Tetracycline and Macrolide Antibiotics in Activated Sludge Process and Their Subsequent Removal during Sludge Reduction by Ozone. *Chemosphere* **2018**, *206*, 184–191.

(3) Scholz, M. Chapter 15 - Activated Sludge Processes. In *Wetlands for Water Pollution Control*, 2nd ed.; Scholz, M., Ed.; Elsevier, 2016; pp 91–105.

(4) McIarty, P. L.; Bae, J.; Kim, J. Domestic Wastewater Treatment as a Net Energy Producer—Can This Be Achieved? *Environ. Sci. Technol.* **2011**, *45* (17), 7100–7106.

(5) Tchobanoglous, G.; Burton, F.; Stensel, H. D. Wastewater Engineering: Treatment and Reuse. *Am. Water Work. Assoc. J.* **2003**, *95* (5), 201.

(6) Jonasson, M. *Energy Benchmark for Wastewater Treatment Processes*. M.S. Thesis, Dept. of Industrial Electrical Engineering and Automation, Lund University: Lund, Sweden, 2007.

(7) Gude, V. G. Energy and Water Autarky of Wastewater Treatment and Power Generation Systems. *Renewable Sustainable Energy Rev.* **2015**, *45*, 52–68.

(8) Goldstein, R.; Smith, W. *Water and Sustainability: U.S. Electricity Consumption for Water Supply and Treatment—The Next Half Century*, Electric Power Research Institute, 2002; Vol. 4.

(9) Shen, Y.; Linville, J. L.; Urgun-Demiratas, 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. *Renewable Sustainable Energy Rev.* **2015**, *50*, 346–362.

(10) He, Z. Microbial Fuel Cells: Now Let Us Talk about Energy. *Environ. Sci. Technol.* **2013**, *47* (1), 332–333.

(11) Plappally, A.K.; Lienhard, J. V. H. Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal. *Renewable Sustainable Energy Rev.* **2012**, *16* (7), 4818–4848.

(12) Shizaz, I.; Bagley, D. M. Experimental Determination of Energy Content of Unknown Organics in Municipal Wastewater Streams. *J. Energy Eng.* **2004**, *130* (2), 45–53.

(13) Heidrich, E. S.; Curtis, T. P.; Dolfing, J. Determination of the Internal Chemical Energy of Wastewater. *Environ. Sci. Technol.* **2011**, *45* (2), 827–832.

(14) Verstraete, W.; Vlaeminck, S. E. ZeroWasteWater: Short-Cycling of Wastewater Resources for Sustainable Cities of the Future. *Int. J. Sustain. Dev. World Ecol.* **2011**, *18* (3), 253–264.

(15) Laureni, M.; Falas, P.; Robin, O.; Wick, A.; Weissbrödt, D. G.; Nielsen, J. L.; Ternes, T. A.; Morgenroth, E.; Joss, A. Mainstream Partial Nitritation and Anammox: Long-Term Process Stability and Effluent Quality at Low Temperatures. *Water Res.* **2016**, *101*, 628–639.

(16) Sarpong, G.; Gude, V. G.; Magbanua, B. S. Energy Autarky of Small Scale Wastewater Treatment Plants by Enhanced Carbon Capture and Codigestion—A Quantitative Analysis. *Energy Convers. Manage.* **2019**, *199*, 119999.

(17) Sarpong, G.; Gude, V. G.; Magbanua, B. S.; Truax, D. D. Evaluation of Energy Recovery Potential in Wastewater Treatment Based on Codigestion and Combined Heat and Power Schemes. *Energy Convers. Manage.* **2020**, *222*, 113147.

(18) Gude, V. G. Energy Positive Wastewater Treatment and Sludge Management. *Edorium J. Waste Manag.* **2015**, *1*, 10–15.

(19) Strous, M.; Van Gerven, E.; Zheng, P.; Kuenen, J. G.; Jetten, M. S. M. Ammonium Removal from Concentrated Waste Streams with the Anaerobic Ammonium Oxidation (Anammox) Process in Different Reactor Configurations. *Water Res.* **1997**, *31* (8), 1955–1962.

(20) Kartal, B.; Van Nitrifk, L.; Ratratty, J.; Van De Vossenberg, J. L. C. M.; Schmid, M. C.; Sinninghe Damsté, J.; Jetten, M. S. M.; Strous, M. Candidatu s ’Brocadia Fulgida’: An Autofluorescent Anaerobic Ammonium Oxidizing Bacterium. *FEMS Microbiol. Ecol.* **2008**, *63* (1), 46–55.

(21) Kartal, B.; Kuenen, J. G. v; Van Loosdrecht, M. C. M. Sewage Treatment with Anammox. *Science (Washington, DC, U. S.*) **2010**, *328* (3979), 702–703.

(22) Jetten, M. S. M.; Horn, S. J.; van Loosdrecht, M. C. M. Towards a More Sustainable Municipal Wastewater Treatment System. *Water Sci. Technol.* **1997**, *35* (9), 171–180.

(23) Pynaert, K.; Smets, B. F.; Wyffels, S.; Beheydt, D.; Siciliano, S. D.; Verstraete, W. Characterization of an Autoctrophic Nitrogen-Removing Biofilm from a Highly Loaded Lab-Scale Rotating Biological Contactor. *Appl. Environ. Microbiol.* **2003**, *69* (6), 3626–3635.

(24) Sziekers, A. O.; Derwort, N.; Gomez, J. L. C.; Strous, M.; Kuenen, J. G.; Jetten, M. S. M. Completely Autotrophic Nitrogen Removal over Nitrite in One Single Reactor. *Water Res.* **2002**, *36* (10), 2475–2482.

(25) Abma, W. R.; Driessen, W.; Haarhuis, R.; Van Loosdrecht, M. C. M. Upgrading of Sewage Treatment Plant by Sustainable and Cost-Effective Separate Treatment of Industrial Wastewater. *Water Sci. Technol.* **2010**, *61* (7), 1715–1722.

(26) Van der Star, W. R. L.; Abma, W. R.; Blommers, D.; Mulder, J.-W.; Tokutomi, T.; Strous, M.; Picoreanu, C.; Van Loosdrecht, M. C. M. Startup of Reactors for Anoxic Ammonium Oxidation: Experiences from the First Full-Scale Anammox Reactor in Rotterdam. *Water Res.* **2007**, *41* (18), 4149–4163.

(27) Li, Y.; Klaus, S.; Bott, C.; He, Z. Status, Challenges, and Perspectives of Mainstream Nitritation–Anammox for Wastewater Treatment: Li et Al. *Water Environ. Res.* **2018**, *90* (7), 634–649.

(28) Rittmann, B. E. Microbial Ecology to Manage Processes in Environmental Biotechnology. *Trends Biotechnol.* **2006**, *24* (6), 261–266.

(29) Li, Y.; Williams, I.; Xu, Z.; Li, B.; Li, B. Energy-Positive Nitrogen Removal Using the Integrated Short-Cut Nitrification and Autotrophic Denitriﬁcation Microbial Fuel Cells (MFCs). *Appl. Energy* **2016**, *163*, 352–360.

(30) Arias, D. M.; Solé-Bundó, M.; Garfí, M.; Ferrer, I.; Garcia, J.; Uggetti, E. Integrating Microalgae Tertiary Treatment into Activated Sludge Systems for Energy and Nutrients Recovery from Wastewater. *Bioresour. Technol.* **2018**, *247*, 513–519.

(31) Ely, C.; Rock, S. Food Waste to Energy: How Six Water Resource Recovery Facilities Are Boosting Biogas Production and the Bottom Line; EPA/600/R-14/240; U.S. Environmental Protection Agency: Washington, DC, 2014.

(32) Stewart, D. *Case Studies in Residual Use and Energy Conservation at Wastewater Treatment Plants*; National Renewable Energy Laboratory: Golden, CO, 1995.

(33) Wiser, J.; Schettler, J.; Willis, J. *Evaluation of Combined Heat and Power Technologies for Wastewater Facilities*, EPA 832-R-10-006; Dec. 2010.

(34) Shi, C. Y. Mass Flow and Energy Efﬁciency of Municipal Wastewater Treatment Plants; IWA Publishing, 2011.

(35) Gude, V. G. Wastewater Treatment in Microbial Fuel Cells—an Overview. *J. Cleaner Prod.* **2020**, *122*, 287–307.

(36) Rosenbaum, M.; He, Z.; Angenent, L. T. Light Energy to Bioelectricity: Photosynthetic Microbial Fuel Cells. *Curr. Opin. Biotechnol.* **2010**, *21* (3), 259–264.

(37) Van de Graaf, A. A.; de Bruijn, P.; Robertson, L. A.; Jetten, M. S. M.; Kuenen, J. G. Autotrophic Growth of Anaerobic Ammonium-Oxidizing Micro-Organisms in a Fluidized Bed Reactor. *Microbiology* **1996**, *142* (8), 2187–2196.

(38) Schmidl, I.; Sziekers, O.; Schmid, M.; Bock, E.; Fuerst, J.; Kuenen, J. G.; Jetten, M. S. M.; Strous, M. New Concepts of Microbial Treatment Processes for the Nitrogen Removal in Wastewater. *FEMS Microbiol. Rev.* **2003**, *27* (4), 481–492.

(39) Kokabian, B.; Gude, V. G. Sustainable Photosynthetic Bioelectrode in Microbial Desalination Cells. *Chem. Eng. J.* **2015**, *262*, 958–965.
(40) Kokabian, B.; Smith, R.; Brooks, J. P.; Gude, V. G. Bioelectricity Production in Photosynthetic Microbial Desalination Cells under Different Flow Configurations. *J. Ind. Eng. Chem.* 2018, 58, 131−139.

(41) Kokabian, B.; Ghimire, U.; Gude, V. G. Water Deionization with Renewable Energy Production in Microalgae - Microbial Desalination Process. *Renewable Energy* 2018, 122, 354−361.

(42) Ali, M.; Okabe, J. P. Anammox-Based Technologies for Nitrogen Removal: Advances in Process Start-up and Remaining Issues. *Chemosphere* 2015, 141, 144−153.

(43) Siegrist, H.; Salzgeber, D.; Eugster, J.; Joss, A. Anammox Brings WWTP Closer to Energy Autarky Due to Increased Biogas Production and Reduced Aeration Energy for N-Removal. *Water Sci. Technol.* 2008, 57 (3), 383−388.

(44) Wett, B.; Buchauer, K.; Fimml, C. Energy Self-Sufficiency as a Feasible Concept for Wastewater Treatment Systems. *Proceedings of IWA Leading Edge Technology Conference; Asian Water*, Singapore, Sept. 21−24, 2007.

(45) Wett, B. Development and Implementation of a Robust Deammonification Process. *Water Sci. Technol.* 2007, 56 (7), 81−88.

(46) Caliskaner, O.; Tchobanoglous, G.; Reid, T.; Davis, B.; Young, R.; Downey, M. First Full-Scale Installation of Primary Filtration for Advanced Primary Treatment to Save Energy and Increase Capacity. *Proc. Water Environ. Fed.* 2017, 2017 (7), 4241−4254.

(47) Sarpong, G.; Gude, V. G. Near Future Energy Self-sufficient Wastewater Treatment Schemes. *Int. J. Environ. Res.* 2020, 14, 479−488.

(48) Kokabian, B.; Gude, V. G.; Smith, R.; Brooks, J. P. Evaluation of Anammox Biocathode in Microbial Desalination and Wastewater Treatment. *Chem. Eng. J.* 2018, 342, 410−419.

(49) Ghimire, U.; Gude, V. G. Accomplishing a NEW (Nutrient-Energy-Water) Synergy in a Biocatalytic Nitritation-Anammox Process. *Sci. Rep.* 2019, 9 (1), 9201.

(50) Li, W.-W.; Yu, H.-Q.; He, Z. Towards Sustainable Wastewater Treatment by Using Microbial Fuel Cells-Centered Technologies. *Energy Environ. Sci.* 2014, 7 (3), 911−924.

(51) Lackner, S.; Gilbert, E. M.; Vlaeminck, S. E.; Joss, A.; Horn, H.; van Loosdrecht, M. C. M. Full-Scale Partial Nitritation/Anammox Experiences—an Application Survey. *Water Res.* 2014, 55, 292−303.

(52) Hao, X.; Li, J.; van Loosdrecht, M. C. M.; Jiang, H.; Liu, R. Energy Recovery from Wastewater: Heat over Organics. *Water Res.* 2019, 161, 74−77.

(53) Dai, W.; Xu, X.; Liu, B.; Yang, F. Toward Energy-Neutral Wastewater Treatment: A Membrane Combined Process of Anaerobic Digestion and Nitritation-Anammox for Biogas Recovery and Nitrogen Removal. *Chem. Eng. J.* 2015, 279, 725−734.

(54) Darrow, K.; Tidball, R.; Wang, J.; Hampson, A. *Catalog of CHP Technologies*; U.S. EPA, 2017.

(55) Dhanya, B. S.; Mishra, A.; Chandel, A. K.; Verma, M. L. Development of Sustainable Approaches for Converting the Organic Waste to Bioenergy. *Sci. Total Environ.* 2020, 723, 138109.

(56) Wang, Q. A Roadmap for Achieving Energy-Positive Sewage Treatment Based on Sludge Treatment Using Free Ammonia. *ACS Sustainable Chem. Eng.* 2017, 5 (11), 9630−9633.

(57) Nordahl, S. L.; Devkota, J. P.; Amirebrahimi, J.; Smith, S. J.; Breuning, H. M.; Preble, C. V.; Satchwell, A. J.; Jin, L.; Brown, N. J.; Kirchstetter, T. W.; Scown, C. D. Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies. *Environ. Sci. Technol.* 2020, 54 (15), 9200−9209.

(58) Kapoor, R.; Ghosh, P.; Kumar, M.; Sengupta, S.; Gupta, A.; Kumar, S. S.; Vijay, V.; Kumar, V.; Kumar Vijay, V.; Pant, D. Valorization of Agricultural Waste for Biogas Based Circular Economy in India: A Research Outlook. *Bioresour. Technol.* 2020, 304, 123036.

(59) Sarpong, G.; Gude, V. G. Codigestion and combined heat and power systems energize wastewater treatment plants—Analysis and case studies. *Renewable Sustainable Energy Rev.* 2021, 144, 110937.