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# Energy and nutrient recovery for municipal wastewater treatment: How to design a feasible plant layout?

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ABSTRACT

Activated sludge systems are commonly used for robust and efficient treatment of municipal wastewater. However, these systems cannot achieve their maximum potential to recover valuable resources from wastewater. This study demonstrates a procedure to design a feasible novel configuration for maximizing energy and nutrient recovery. A simulation model was developed based on literature data and recent experimental research using steady-state energy and mass balances with conversions. The analysis showed that in the Netherlands, proposed configuration consists of four technologies: bioflocculation, cold partial nitritation/Anammox, P recovery, and anaerobic digestion. Results indicate the possibility to increase net energy yield up to 0.24 kWh/m$^3$ of wastewater, while reducing carbon emissions by 35%. Moreover, sensitivity analysis points out the dominant influence of wastewater organic matter on energy production and consumption. This study provides a good starting point for the design of promising layouts that will improve sustainability of municipal wastewater management in the future.

## 1. Introduction

Biological treatment of municipal wastewaters is mostly accomplished in conventional activated sludge (CAS) systems. This also holds for municipal wastewater treatment in the Netherlands (Stowa, 2010). A CAS system is designed to produce an effluent that meets the discharge guidelines by removing organic pollutants and the nutrients, nitrogen (N) and phosphorus (P). Although CAS systems are very robust, they cannot be considered sustainable. A major drawback is the high energy consumption, mainly for aeration which accounts for about half of the total energy consumption of 0.6 kWh per m$^3$ of wastewater (McCarty et al., 2011). Municipal wastewaters with typical organic matter concentrations (expressed in chemical oxygen demand or COD) of 400–500 mg COD/L (Owen, 1982) contain a potential chemical energy of 1.5–1.9 kWh per m$^3$ of wastewater, which is more than twice the energy demand of a typical CAS system. In a CAS system this energy is largely destroyed by aerobic mineralization of the sewage organic matter to $CO_2$. Another drawback is that no N and P, and only a limited amount of energy contained in the organic pollutants, are recovered. The commonly used processes for nutrient removal are biological nitrification/denitrification for N-removal and chemical or biological P-removal. These processes result in a loss of N and P. In particular P that comes from mines and can become scarce in the future, whereas $N_2$ is abundantly available in the atmosphere (De Ridder et al., 2012; Schröder et al., 2010). Therefore, P in municipal wastewater is considered a valuable source for possible reuse as a fertilizer. For example, de Graaff et al. (2011) reported that the total amount of P that can be found in Dutch municipal wastewater corresponds to more than 50% of the artificial P fertilizer used in the country.

Several novel sustainable wastewater treatment and resources recovery technologies are available; however, little is known about how to integrate such technologies in municipal wastewater treatment plants (WWTPs). Therefore, a simulation approach could be an appropriate tool to develop new configurations for future municipal WWTPs and to predict the feasibility of these configurations. Such an approach has already been used for different applications, for example, for separation at source configurations in which urine and black water are separately treated (Tervahauta

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et al., 2013; Wilsenach and van Loosdrecht, 2006), for water treatment configurations based on microalgae biofilms (Boelee et al., 2012), for optimizing the urban water infrastructure systems (Agudelo-Vera et al., 2012; Hiessl et al., 2001), for development of a benchmarking methodology for advanced control in oxidation ditch municipal WWTPs (Abusam, 2001), and for identifying the future potential energy contribution from wastewater (Heubeck et al., 2011). However, limited information can be found in the literature on integration of both treatment and resource recovery perspectives on the future of municipal WWTPs, whereas municipal wastewater can be considered as a valuable source of water and nutrients in agriculture (Verstraete et al., 2009). Also, knowledge-based decision support systems (DSSs) and life cycle assessment (LCA) methods are used to facilitate an appropriate or optimal WWTP design with different objectives and requirements. However, so far these are limited to conventional wastewater treatment systems and the results are largely dependent on the data quality and their specifications (Aulinas et al., 2011; Garrido-Baserba et al., 2014; Rivas et al., 2008; Wang et al., 2012).

The objective of this study is to introduce and demonstrate a quantitative procedure to analyze future municipal WWTPs that minimize energy input and $CO_2$ emissions, maximize energy production and recovery of valuable nutrients, and meet the effluent discharge guidelines. The Excel-based simulation tool presented in this study allows investigation of the feasibility of novel configurations for municipal wastewater treatment. For this purpose these configurations are compared to a reference CAS system based on several performance indicators related to conditions in the Netherlands/Western Europe. Additionally, a sensitivity analysis is performed for temperature and wastewater characteristics to extrapolate the results to other countries and climate regions.

## 2. Material and methods

An Excel-based model was developed, based on literature data and on information from laboratory scale experiments with selected wastewater treatment and recovery processes. In this study, to compare new configurations with the reference CAS system, the model was constructed from available removal, and recovery efficiencies under steady-state conditions. As our focus is on design, and not monitoring and control, kinetics and time variations were not yet part of this study.

### 2.1. Potential integrated treatment processes

Potential sustainable wastewater treatment and recover processes considered in this study were: i) the subsequent bioflocculation, anaerobic digestion, and combined heat and power (CHP), ii) cold partial nitritation/Anammox, iii) P recovery technology, and iv) microalgae biofilms with the removal of COD. In this study P recovery is expressed in terms of an assumed recovery efficiency. For an overview of P recovery technologies, we refer to de-Bashan and Bashan (2004).

#### 2.1.1. Bioflocculation, anaerobic sludge digestion, and CHP

Bioflocculation is a possible technique to concentrate sewage organic matter, similar to the A-stage in an AB process design (Boehnke et al., 1997). Aerobic microorganisms produce extracellular polymer substances (EPS) that facilitate the flocculation between the microorganisms and sewage organic matter (Salehizadeh and Shojaosadati, 2001). Bioflocculation of municipal wastewater results in a concentrated stream of sewage organic matter, from which methane can be produced by anaerobic sludge digestion (Akanyeti et al., 2010). To separate the organic sludge from the effluent, a settler or a membrane can be used. In this study, a settler is chosen due to its simplicity with low operational and maintenance cost. In addition, the underflow of the settler is further dewatered using a thickener to achieve the desired concentration of bioflocculation concentrate before digestion. Subsequently, a CHP unit is used to produce energy and heat from the methane formed in the anaerobic digestion. The removal and conversion efficiencies and design specifications of the integrated bioflocculation, anaerobic digestion and CHP process are presented in Table 1.

#### 2.1.2. Cold partial nitritation/Anammox

Partial nitritation/Anammox process is a more sustainable process than subsequent nitrification and denitrification processes applied in the CAS system. In the partial nitritation stage, ammonium is partly nitrified to nitrite (Giusti et al., 2011). In the Anammox stage, the produced nitrite is subsequently denitrified in combination with the residual ammonium to form nitrogen gas and nitrate (Cui, 2012). It is important to note that about half of the ammonium should convert into nitrite during the partial nitritation, so that the nitrite-to-ammonium ratio in the effluent will be about 1.3:1 as required for Anammox process. This optimal ratio can be obtained by control of the sludge retention time (SRT), alkalinity, and/or oxygen concentration. Some research models have used an alkalinity/ammonium ratio

**Table 1**
Efficiency, conversion and design parameter values for bioflocculation, anaerobic sludge digestion, and CHP process.

| Process | Unit | Value used | Reference |
|---|---|---|---|
| **Bioflocculation** | | | |
| Total COD removal efficiency[e] | %CODtotal | 80 | Akanyeti et al. (2010) |
| COD substrate need for biomass growth | % CODbs[d] | 40 | Design parameter |
| $O_2$ need | g $O_2$/g $\text{CODbs}_{\text{removed}}$ | 0.51[a] | – |
| $CO_2$ production | g $CO_2$/g $\text{CODbs}_{\text{removed}}$ | 0.70[a] | – |
| Biomass yield | g VSS/g $\text{CODbs}_{\text{removed}}$ | 0.40 | Metcalf and Eddy (2004) |
| COD in biomass | g COD/g VSS[d] | 1.42 | Metcalf and Eddy (2004) |
| N in biomass | g N/g VSS | 0.124 | Metcalf and Eddy (2004) |
| P in biomass | g P/g VSS | 0.027 | Metcalf and Eddy (2004) |
| Thickener capacity | g COD/L | 50 | Design parameter |
| **Anaerobic sludge digestion** | | | |
| Total COD removal efficiency | % CODb[d] | 70 | Cakir and Stenstrom (2007) |
| Methane production (digestion) | g $CH_4$/g $\text{COD}_{\text{removed}}$ | 0.23[b] | – |
| $CO_2$ production | g $CO_2$/g $\text{COD}_{\text{removed}}$ | 0.64[b] | – |
| Biomass yield | g VSS/g $\text{COD}_{\text{removed}}$ | 0.058[b] | Metcalf and Eddy (2004) |
| COD, N, P in biomass (see bioflocculation) | | | |
| **CHP** | | | |
| Electricity recovery | % | 38 | Verstraete and Vlaeminck (2011) |
| Heat recovery | % | 40 | Verstraete and Vlaeminck (2011) |
| Energy loss | % | 22 | – |
| $CO_2$ production | g $CO_2$/g $CH_4$[d] | 2.75[c] | – |
| Enthalpy of combustion | kWh/kg $CH_4$ | 13.9 | H2moves.eu (2006) |

[a] Assuming acetate as organic matter (1.07 g COD/g acetate), the following stoichiometric equation is used for aerobic, heterotrophic oxidation of organic matter (Metcalf and Eddy, 2004): $5CH_3COO^- + NH_4^+ + 5O_2 \rightarrow C_5H_7O_2N + 4H_2O + 5CO_2 + 4OH^-$.

[b] Assuming acetate as COD the following stoichiometric equation is used for anaerobic digestion (Gavala et al., 2003): $CH_3COO^- + 0.032NH_4^+ + 0.968H^+ \rightarrow 0.92CH_4 + 0.92CO_2 + 0.032C_5H_7O_2N + 0.096H_2O$.

[c] The following stoichiometric reaction is used for converting methane to heat and power (Wett et al., 2007). $0.5CH_4 + O_2 \rightarrow 0.5CO_2 + H_2O$ + heat + energy.

[d] Chemical oxygen demand (COD), biodegradable COD (CODb), biodegradable soluble COD (CODbs), methane ($CH_4$), and biomass expressed in volatile suspended solids (VSS).

[e] Data from lab-scale high-loaded membrane bioreactor conducted at temperature 20 °C (Akanyeti et al., 2010).