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Analysis of Greenhouse Gas Emissions from an Activated Sludge Wastewater Treatment Technology

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Abstract: Prediction of the greenhouse gas emissions (GHGs) of wastewater treatment plants (WWTPs) is essential for carrying out life cycle analysis of a pollutant. Meeting the effluent quality requirement for liquid phase is based on the regulations, but due to the process conversion products from the wastewater appear in the gaseous phase. An estimation of GHG emissions is the first step to apply process control and optimisation. In this study a middle-sized WWTP in Hungary was examined and based on analytical methods to emission was predicted. Environmental and process variables were also taken into account and the effect on the GHG emission was analysed.

Keywords: Activated sludge, Bridle model, Greenhouse gas, Wastewater treatment

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I. INTRODUCTION

Increased attention is being paid to greenhouse gas emissions worldwide. These gases prevent heat from escaping into the atmosphere, resulting in increased temperatures near the earth surface. Various economic incentives have been introduced to reduce greenhouse gas emissions. Therefore, there is considerable interest in determining the carbon footprint of wastewater treatment plants. This requires consideration of greenhouse gas emissions, energy use, energy production and carbon production. Quantities of these gases can be predicted mainly in equivalent mass of CO_2 measured in kilogram. Global Warming Potential (GWP) is introduced for the summation of the effect of various gases emitted. The GWP of a greenhouse gas shows how much one unit of gas contributes to trapping heat radiation compared to one unit of CO_2. The IPPC (Integrated Pollution Prevention and Control) [1].

As shown in the table above, GWP assumes significantly variable values for different gases. As a result, gas with a higher GWP but emitted in smaller quantities may have a greater impact on the atmosphere than a gas with a lower GWP. For example, the effect of 1 kg of nitrous oxide emitted is equivalent to 296 kg of carbon dioxide emitted. Different models are available to estimate the greenhouse gas emissions of a technology. On the one hand, there are static models, such as the Bridle model, which estimate average emissions over a period of time. On the other hand, there are more complex dynamic models that describe the activated sludge process in detail.

The amount of carbon dioxide and methane produced depends on the organic matter content of wastewater - often characterized by biological oxygen (BOD) and chemical oxygen demand (COD)-, on the temperature of the wastewater, and the technology applied. The amount of nitrous oxide depends mainly on the nitrogen content of the wastewater entering the plant.

The IPPC guidance does not break down emissions estimates into individual technologies/sites, but uses country-specific averages. It starts with the annual organic or nutrient load, and uses this to derive specific emissions from annual emissions. It applies a correction factor for methane depending on the aerobic activity of the system; for nitrous oxide a specific load type value of 3.2 g N_2O/person/day is used. This method is subject to considerable uncertainty, but is also a fast data estimator with low data requirements.

In the following, some of the greenhouse gas emission estimation methods developed for wastewater treatment plants are summarized, ranging from assumptions using simple specific values to biokinetic models. Description of models is followed by a calculation of an existing plant using activated sludge. Operational data from the plant were analyzed and based on literature review estimation and evaluation of GHG emission were carried out. In addition to state analysis of the plant, recommendations were made for optimal operation.

Wastewater treatment is responsible for the degradation of organic matter and removal of nutrients (nitrogen and phosphorous). The various nitrogen forms are the bottleneck of the treatment. Nitrogen is present in wastewater as complex organic compounds or as ammonium, nitrite, and nitrate. Amino acids and proteins are converted to ammonium in the sewer system and in the biological reactor by microbial degradation. In conventional BNR (Biological Nutrient Removal) process, ammonium is first converted to nitrite and then nitrate by autotrophic bacteria and then nitrogen gas is formed by heterotrophic denitrifiers. The bioreactor applied for nitrogen removal is designed by taking into consideration the requirements of nitrification and denitrification processes: nitrification takes place under aerobic conditions, whereas denitrification requires anoxic environment and organic carbon source throughout the process. To achieve this, the BNR reactor arrangements are suitable for continuous operation and the entire reactor volume is separated into two zones where nitrification and denitrification can take place. In a typical MLE (Modified-Ludzack-Ettinger) reactor arrangement, the aerobic zone is preceded by the anoxic zone [2]. At the end of the aerobic zone, wastewater containing nitrate is recycled back to the anoxic compartment. The amount of wastewater recycled can be many times more than the amount of wastewater discharged. SRT (Solids Retention Time) can show large variety from 10 to 30 days.

There are several variations of this configuration. For example, an additional anoxic-aerobic reactors can be added to the process forming a four-stage anoxic-aerobic-anoxic-aerobic reactor series. In this arrangement, both the first and second anoxic zones require the addition of external carbon source - raw wastewater or methanol - to provide the organic carbon required for denitrification. In these configurations, activated sludge often flows between the anoxic and aerobic zones. The concentration of dissolved oxygen (DO) in the aerobic zone is at least 1.8-2.0 mg/l, although it may be outside these range where automatic DO control is not applied. In comparison, the value of dissolved oxygen in the anoxic zone is negligible, its value is close to zero. Dissolved oxygen is presented in this system due to recirculation and/or naturally absorbed through the water surface. Another BNR solution is oxidation ditch. Horizontal brush aerators (Kessener brushes) are placed in the oxidation ditch, which ensures proper oxygen transport and wastewater flows at relatively high speeds (0.3-0.5 m/s). Complete mixing of wastewater in the oxidation ditch usually takes a few minutes.

Zones with high dissolved oxygen concentrations may develop near the aerators. Anoxic zones develop in areas farther from the aerators. High recirculated wastewater flow and increased tank capacity provide more stable conditions than the MLE process. As an additional function of the oxidation ditch, dissolved oxygen concentration is typically low (0.5 mg/l), favoring simultaneous nitrification and denitrification. Inside the activated sludge flocs oxygen concentration gradient develops, resulting various conditions (aerobic, anoxic) inside the flocs and diffusion limitation for nitrification and denitrification. Therefore, nitrifiers are attached to the outer layer of the flocs, where oxygen supply is adequate, while denitrifiers can provide simultaneous denitrification and nitrification under anoxic conditions inside the flocs.

Batch activated sludge systems are also capable of removing nitrogen and organic carbon. In this case, aerobic and anoxic conditions are separated by time and not by space. The entire process takes place in one single reactor and the aeration is intermittent.

II. MATERIAL AND METHODS

The United Nations has defined three categories of greenhouse gas emissions from an industrial technology. The first category includes direct greenhouse gas emissions from the plant. The second category is direct emissions and indirect emissions from the production of electricity for operating the plant. The latter is not actually emitted at the test site, but at the place where electricity is generated, but since the test plant uses the generated electricity it should be added to its total output [3]. For a sewage treatment plant, this would include the energy used for aeration. The third category includes first and second category emissions and other indirect greenhouse gas emissions. This applies to emission sources that are not owned or influenced by the site under study, e.g. emissions from the manufacture of chemicals used in the plant fall into this category. In order to estimate the total greenhouse gas emissions of a sewage treatment plant, the listed emissions must be taken into account in a manner comparable to other plants.

Required emissions from the three categories based on the Bridle model are as follows:

1. CO_2 and N_2O emissions from biological treatment, internal recirculation, BOD oxidation, nitrification, CO_2, and N removal
2. Energy use of aeration, mixing, and operating pumps
3. Sludge digestion, release of biogas (CH_4, CO_2)
4. Disposal of remaining sludge (removal, storage)
5. Use of biogas
6. Applied chemicals

Certain emissions are not taken into account in the model. These include indirect emissions by employees, such as commuting to work or using public transport. This is not taken into account by the model because it is specific and negligible compared to other sources at each site.

III. RESULTS AND DISCUSSION

The Bridle model calculates the decomposition of biomass:

$X_{decay}=Q*HRT*MLVSS*k_d$

where:

X_{decay}: daily biomass degraded [kgVSS/day]

Q: average daily influent volume [m^3/day]

HRT: hydraulic residence time [day]

$MLVSS$: Mixed Liquor Volatile Suspended Solids [kg/m^3]

k_d: endogenous degradation constant [1/day]

The average daily inflow data was provided by the plant. Daily average influent flow was calculated based on six month data series. HRT was calculated as the ratio of the volume of the basin to daily effluent. The average MLVSS value is set to constant in the plant. The endogenous degradation constant is 0.1 L/d in the biological basin. Based on these the daily degraded biomass is 3569 kg VSS/d.

To obtain the carbon dioxide produced from the mass of decomposed biomass, basic stoichiometric assumption was made as follows:

$$C_5H_7O_2N + + 5\ O_2 \rightarrow 5CO_2 + + 2\ H_2O + NH_3$$

It follows that the ratio of CO_2 in biomass to biomass is 113:5*44, which is equal to 1:1.947. This means that one kilogram of biomass produces 1.947 kg of CO_2.

Based on these:

$CO_{2biomass}=X_{decay}*1.947=6949$ kg CO_2/d.

Organic oxidation (BOD oxidation)

$BOD_{ox}=Q*(BOD_{inf}-BOD_{eff})$

where BOD_{ox} is the oxidized amount of BOD, BOD_{inf} is the influent BOD, BOD_{eff} is the effluent BOD. Substituing the formula the total oxidized BOD is 5048 kg/d.

The actual biomass yield can be determined as follows:

$Y_{obs}=Y/(1+k_d*SRT)$

where:

Y_{obs}: actual biomass yield [kg VSS/kg BOD_{rem}]

Y: biomass yield [kg VSS / kg BODrem]

SRT: sludge residence time [day]

The biomass yield was obtained by dividing the daily excess sludge by the daily influent BOD. Excess sludge removal is 3600 kgTS/day, and the daily BOD influent is 5264 kg/day.Therefore the yield is 0.68 kg VSS/kg BOD_{rem}. The sludge residence time in the basin was calculated based on the following formula:

$SRT=MLSS*V/(Q_{was}*DS\%)$

Substituing the formula SRT=10.47 days and, thus, the observed biomass yield is 0.33 kg VSS/kg BOD_{rem}. Actual biomass production can be determined by the multiplication of the observed yield with the oxidized BOD. Thus, the net biomass production (X_{net}) is 1666 kg VSS/d. From the production oxygen consumption can be estimated as follows:

$O_2=BOD_{ox}/f-1.42*X_{net}$

$O_2=5048/0.66-1.42*1666=5283$ kgO_2/d

If the daily oxygen consumption is known, the amount of CO_2 produced per day can be calculated assuming the conversion ratio between the oxidised biomass and CO_2 production. Since the ratio comes from stoichiometry, it is relatively constant and has the value of 1.1, resulting in a daily emission of 5811kg CO_2 due to oxidised BOD. The final step in calculating biological treatment GHG emission is nitrogen removal. Ammonium removal uses CO_2 which leads to CO_2 credit. Denitrification produces CO_2 and N_2O. The amount of nitrogen in the biomass is calculated from the elemental composition of the biomass. The molar mass of nitrogen is 14 and that of biomass is 113. Consequently, the amount of nitrogen in the resulting biomass is as follows:

$N_{biomass} = X_{net}* 14/113= 206$ kg N/d

Amount of oxidized ammonia can be calculated by the nitrified TKN fraction, which is based on the difference of the influent and effluent TKN corrected by the biomass nitrogen uptake. Assuming the average influent, oxidised ammonium is 1145 kg N/s

Calculation of CO_2 credit from the amount of oxidised ammonia is based on the previously estimated oxidised ammonium and a stoichiometry ratio of 4.49. Thus, the CO_2 credit is 5141 kg CO_2/d.

N_2O emission of nitrogen removal can be calculated by multiplication of the incoming nitrogen and N_2O production ratio (0.012). Thus, N_2O is 20 kgN_2O/d. By multiplying this value by the global warming potential, N_2O emissions is converted to CO_2 emissions. This results 5920 kg CO_2/d. Total CO_2 emission from biological treatment is the summation of the four terms (biomass decay, BOD oxidation, CO_2 credit from nitrification, and N_2O emission). This results 13 540 kg CO_2/d.

The total greenhouse gas emissions of the plant are obtained by adding the emissions from biological treatment to the emissions from energy use. Biotreatment has 13 540 kg CO_2/d, indirect emissions are 3715 kg CO_2/d. By summing the two terms it is 17 255 kg CO_2/d. Normalizing the result with the incoming flow (in other words, the plant capacity), the relative value of CO_2 emission can be gained. During the treatment of 1 m^3 of wastewater 0.78 kg CO_2 is released.

Based on the literature it is recommended to keep this value below 0.5 kg CO_2/m^3 in case of a biogas plant with digester [4]. In other studies, 0.23-0.25 kg CO_2/m^3 were obtained, but in this case only the decomposition of organic matter was investigated without energy consumption and other factors [5]. The quality of effluent also has a major influence on the level of discharge. A study investigated industrial wastewater from food processing, which has high organic matter concentration and will therefore result in a much higher discharge [6]. During Chai's research 2.69 kg CO_2/m^3 was obtained. The wastewater arriving to this particular wastewater treatment plant has a relatively high total nitrogen concentration and organic load. This greatly contributes to the high level of emissions during biological treatment. In other studies total nitrogen concentration was 45 mg/l whereas the average nitrogen concentration in the influent was 131 mg/l [6]. This significantly increases greenhouse gas emissions because high nitrogen concentrations produce more nitrous oxide and have a high global warming potential.

IV. CONCLUSIONS

In the course of the studies, greenhouse gas emission of a semi-scale wastewater treatment technology with a fixed bed biofilm carrier under various operating parameters was examined. For the calculations a GHG emission estimator algorithm based on the biokinetic model was used. For model calibration, a series of measurements was performed on a semi-industrial reactor cascade. In all cases, simulation results show that direct gas emissions from biological origin are more significant than indirect ones from energy use. Increasing the reactor volume results in a higher hydraulic residence time; thus, at lower effluent concentrations, it also results in significantly less nitric oxide gas release due to more efficient nitrification and denitrification, and only slightly increases other indirect emissions (carbon dioxide, methane). However, it should be considered to use larger volumes of biomass than needed to reduce GHG release. An increase in temperature increases the rate of biological reactions; thus, it is favorable in terms of the flow parameters under consideration, but it increases greenhouse gas production, especially nitrous oxide and methane formation. In addition, due to its poor solubility of oxygen, it also slightly increases indirect greenhouse gas emissions. By increasing internal recirculation flow rate, the denitrification process is more efficient, but a reduction in the carbon/nitrogen ratio entering the reactor results in the release of more nitrous oxide. This could increase overall emissions due to increased energy demand of pumping, the other indirect outputs only increase marginally. Increasing dissolved oxygen levels in aerobic reactors slightly increase carbon dioxide emissions; however, this results in increasingly aerobic conditions and less methane and nitrous oxide release, reducing the resulting emissions. Because it is an easily controllable parameter, aeration control can be an effective means of reducing GHG emissions.

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