SUSTAINABILITY EVALUATION OF PHOSPHORUS REMOVAL TECHNIQUES ON MUNICIPAL WASTEWATER TREATMENT PLANTS

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Abstract

Different wastewater treatment plants (WWTPs) process configurations require different amount of resources such as energy and chemicals. The selection of process configuration also impacts the amount of energy produced in the form of biogas.

In this study, Life Cycle Assessment (LCA) has been used to evaluate the environmental impact of operation of three different process configurations for phosphorus removal.

Since every WWTP has their unique conditions it is difficult to compare different WWTPs with each other. To overcome the uniqueness, a dynamic WWTP process models has been used to simulate different process configurations. The model outputs has been used as input data for the LCA.

This paper focus on the results of global warming potential (GWP), also known as carbon footprint. For all process configurations, energy contributes to the highest GWP followed by N_2O release in the biological treatment. Pre-precipitation gives the lowest GWP per volume of treated wastewater and Bio-P gives the highest GWP.

Keywords: carbon footprint, chemical treatment, coagulant, life cycle assessment, phosphorus removal, wastewater treatment.

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1. INTRODUCTION

It is well known that municipal wastewater treatment plants (WWTPs) consume energy in their processes, but also has a potential to produce energy in the form of biogas. There are a number of »standard« process solutions when treating wastewater. The selection of process solution depends on wastewater quality, treatment requirements, available space and perception on what is a good solution or not and, traditional thinking.

With chemical treatment it is possible to remove more phosphorus, produce more biogas, reduce energy consumption in biological treatment and make a more compact plant. Still, chemical treatment is perceived as a less preferred solution in many cases as chemicals comes to a cost and an environmental footprint.

Professor Halvard Ødegaard and Ingemar Karlsson raised this question more than 20 years ago (Ødegaard and Karlsson, 1994; Ødegaard, 1995) and their conclusion was that a combined chemical/biological treatment process is more environmentally friendly than a biological process only. Since then, the Life Cycle Assessments (LCA) tools have been improved, new learnings on how to operate WWTPs are known and technologies have improved. It is therefore of value to, from an LCA perspective, re-evaluate different WWTP processes with the new information available today.

Since every wastewater is unique it is not easy to compare plant A and B with each other. There are not only difference in water quality but also in process design. To compare different process configurations, dynamic process models are advantageous for this type of evaluation since the models can simulated different process configurations but still use the same incoming flow, pollutant load and the yearly. The models can give estimations of resource consumption, effluent concentrations, sludge production and quality and biogas production.

2. OBJECTIVE

The objective with the study was to compare the environmental impact of treating wastewater to two different levels of phosphorus in three different process configurations, using dynamic process modelling and life cycle assessment. The incoming water quality is the same in all scenarios and automatic process control in the models was used to achieve similar treatment results for the different processes.

3. METHOD

To calculate the environmental impact the process layout in combination with process modelling and LCA needs to be in place. This combination is illustrated in Figure 1.

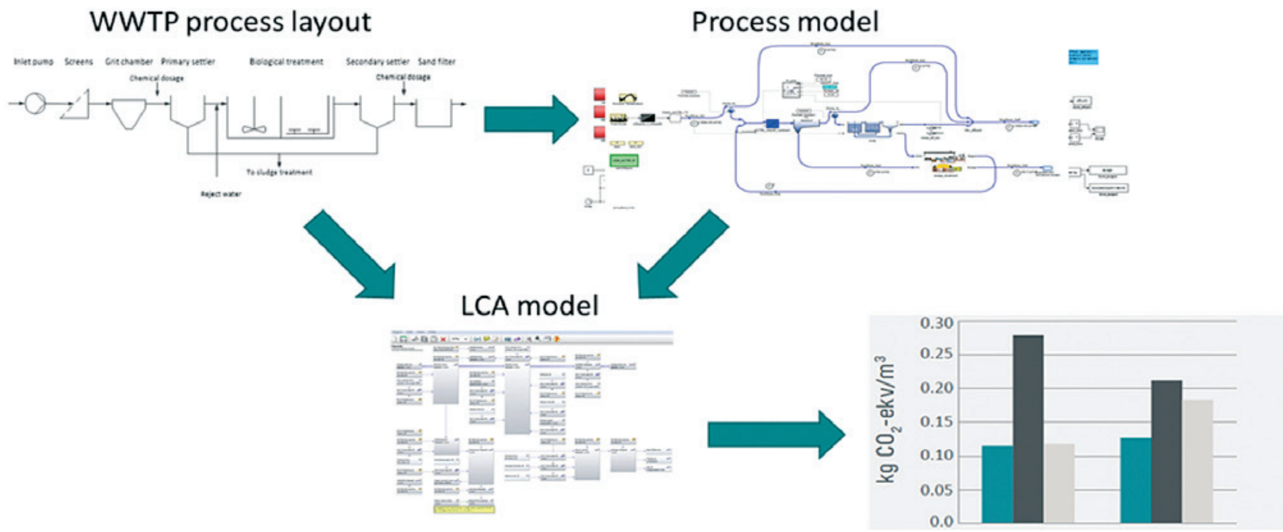

Figure 1: Schematic of the combinations of the different methods.

3.1 Process modelling

The starting point for the process modelling was a full-scale Swedish wastewater treatment plant with a simultaneous precipitation configuration (Henriksdal WWTP, 780 000 P.E., flow 250 MLD (Megaliters per Day)). Data on influent wastewater characteristics, coagulant dosage, sludge production, sludge concentrations, effluent quality, energy data and biogas production were collected and used in calibrating the model. Some adjustments to volumes and operating conditions were done to more resemble standard European conditions.

3.1.1 Effluent discharge criteria

The baseline scenario for the discharge criteria is compliant with the Urban Waste Water Treatment Directive for plants larger than 100 000 P.E. releasing effluent to sensitive areas, (UWWTD, 1991). All discharge limits (Table 1) had to be fulfilled. The three processes configurations were also simulated to reach a lower effluent phosphorus concentration.

Table 1: Effluent discharge criteria as yearly average concentrations.

Scenario	BOD_5	TN	TP
Baseline	25 g/m^3	10 g/m^3	1 g/m^3
Stricter P	25 g/m^3	10 g/m^3	0.3 g/m^3

It should be noted that a Phosphorus removal without chemical addition, so called Biological Phosphorus Removal (Bio-P), is difficult to control to reach a certain effluent standard regarding phosphorous concentration, without a tertiary polishing step. Chemical dosing enables a higher level of control of effluent phosphorous concentration.

3.1.2 Process configuration

In this project three different processes are studied:

1. **Pre-precipitation**. Precipitation chemical is added prior to primary sedimentation.
2. **Simultaneous precipitation.** Precipitation chemical is added in the biological treatment.
3. **Biological Phosphorous Removal.** No precipitation chemical added when possible.

Pre-precipitation gives less load in the biological treatment step and increased biogas production, while simultaneous precipitation has the advantage that incoming carbon source can be used for pre-denitrification but the disadvantage that larger biological volume is needed (to compensate for higher load and that metal in the sludge takes up part of the volume). Bio-P has the advantage that no chemicals are used while the configuration requires larger volumes and more pumping. The aim of the project was to quantify the differences between the configurations in the form of Life Cycle Analysis.

The modelling of the three processes all include primary sedimentation, activated sludge process, secondary sedimentation and anaerobic digestion. Reject water from thickening and dewatering of sludge is added to the inlet (prior to pre-sedimentation). Polymers are added in both the thickening and dewatering of sludge processes. The activated sludge process is a pre-denitrification process without addition of external carbon source. Pre-treatment steps (screens, grit and grease removal) are not included in the dynamic process models.

For the Stricter phosphorus scenario, the process configuration is complemented with sand filtration as a final polishing step after secondary sedimentation. An additional coagulant dosage point is also added just before the sand filters.

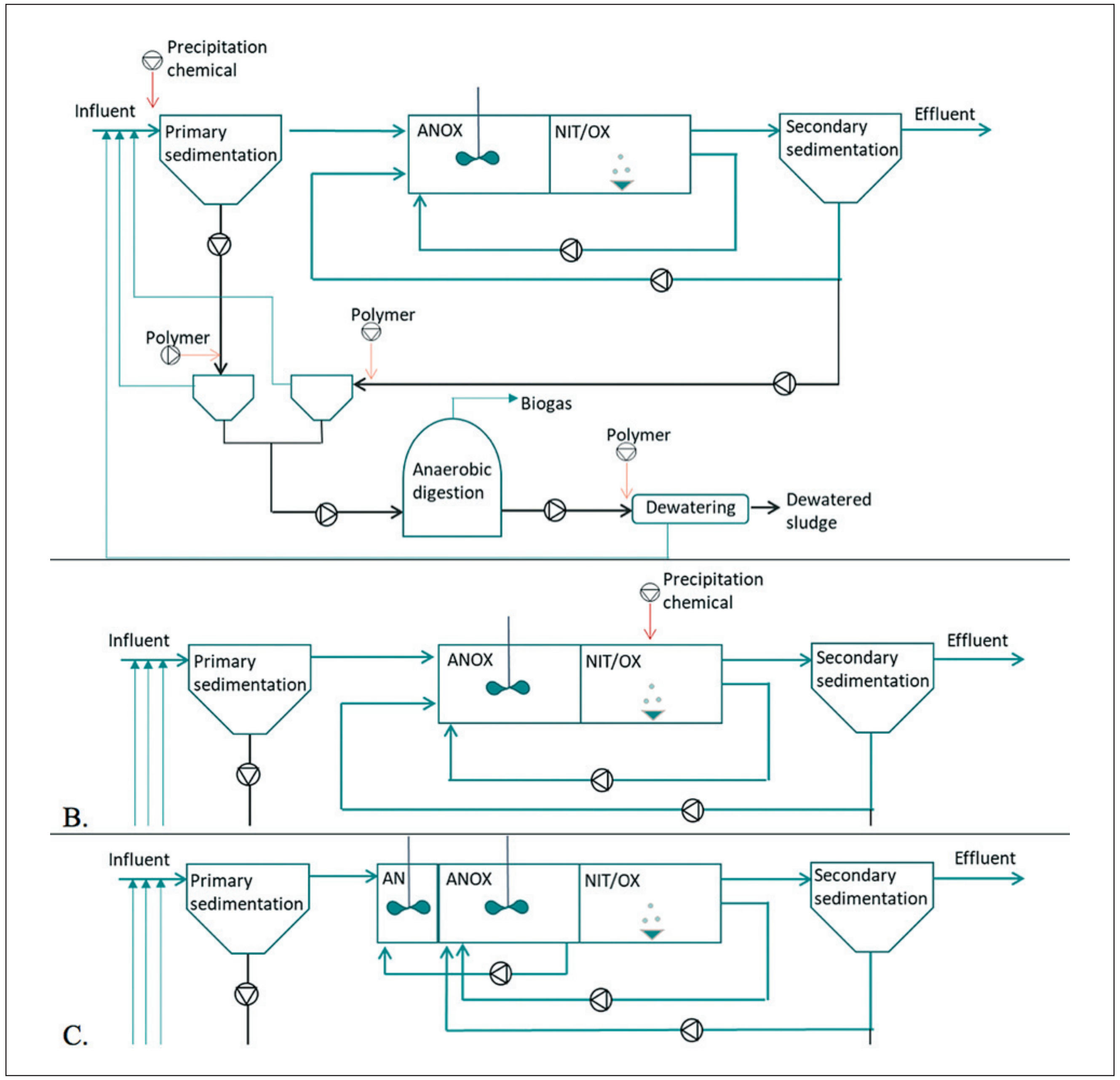

Figure 2: A. Process configuration for Pre-precipitation. **B.** Changes in configuration to simultaneous precipitation. **C.** Changes in configuration to Biological phosphorus removal.

3.1.3 Process volume calculations

The reference plant (Henriksdal WWTP) is operated at a sludge concentration in the biology of about 2 500 g SS/m^3. This is low compared to standard European situations where 4000 g SS/m^3 is normal. To resemble bioreactor volumes with a standard European WWTP a factor 0.625 = 2500/4000 has been used.

With pre-precipitation, the load to the biology will be lower compared to a plant with simultaneous precipitation. Therefore, this alternative has smaller bio-reactor volumes compared to the other two alternatives. With Bio-P removal an additional anaerobic compartment has been added, resulting in a larger total volume for the Activates Sludge Process (ASP). Volumes are found in Table 2.

Table 2: Total volumes used in modelling of the three processes.

Total volumes, m³	Pre-precipitation	Simultaneous precipitation	Bio-P
Primary Sedimentation	30 000	30 000	30 000
AN	N/A	N/A	47 000
ANOX	56 000	56 000	60 000
NIT/OX	30 240	54 000	54 000
Secondary Sedimentation	75 000	75 000	75 000
Anaerobic digester	32 000	28 500	31 000

The hydraulic retention time (HRT) for the anaerobic digester was set to 20 days for all configurations.

3.1.4 Models used

The process modelling has been carried out in the software SIMBA#water. For the biokinetics an extended version of ASM1 (Activated sludge model no 1, Henze et al., 2000) called ASM_inCTRL (Schraa et al., 2016) was used. Anaerobic digestion was modelled using a simple model calculating the biogas production based on biodegradable Chemical Oxygen Demand (COD), temperature, retention time and pH. Sand filtration was modelled with a separate dosage of coagulant on the effluent followed by a fixed separation of solids.

3.1.5 Load

Flow and load are based on data from the reference plant, see Table 3. As it is situated in Sweden, the flow is typical for Nordic conditions, with high infiltration of stormwater runoff and ground water, cold temperatures during winter and a snow-melting period in the spring.

Table 3: Flow and load to the treatment processes as yearly average.

Parameter	Unit	Load, constant	Load, average of dynamic data
Q	m³/d	270 000	250 665
TSS	g/m³	310	313
COD	g/m³	500*	516
TN	g/m³	40	45
TP	g/m³	6	6.7

*TOC measurements x 3.3.

In order to compare the results from the different alternatives priority was set on achieving similar effluent concentrations for each modelled alternative, the same control strategies have been used as seen in Table 4.

Table 4: Different setpoints used in the control of the WWTP.

Scenario	Setpoint TSS Bio (WAS control)	Setpoint Eff NO_3 (Q rec control)	Setpoint Eff PO_4 (Precipitation dosage control)	Setpoint Eff NH_4 (aeration control)
Baseline	< 4000 g/m³	7 g/m³	0.35 g/m³	1 g/m³
Stricter P	< 4000 g/m³	7 g/m³	Addition of sand filter	1 g/m³

3.1.6 Modelling different chemcials

Two types of coagulants are considered; iron and aluminum based. In this paper only the results with ferric chloirde will be presented. For the thickening and dewatering different polymer dosages are used for sludge from different processes. A summary of polymer dosages used can be found in Table 5.

Table 5: The dosage of polymer used for thickening and dewatering as well as DS content and separation degree in the sludge dewatering.

Sludge type	Dosage (g/kg TS)	DS and separation degree in treated sludge (%)
Digested sludge (chemical treated)	11.5*	24 %* 98 % removal
Digested sludge (Bio-P)	16.2*	24 %* 98 % removal

*STOWA 2012

3.2 Life Cycle Assessment - LCA

Life Cycle Assessment (LCA) has been used to calculate the average environmental impact of operation of the WWTP for one year of operation. An LCA includes resource consumption, waste production, energy use and transport for all intermediaries. Construction and demolition of the treatment plant are thus not included.

The life cycle analysis was performed according to ISO 14044 standards and used the GaBi Professional 8.6 software tool to perform the LCA modelling. GaBi Professional has been developed for more than 20 years and contains a robust internal database with more than 7,000 ready-to-use life cycle inventory (LCI) profiles.

The LCA in this study includes activities that are directly related to, or a result of, wastewater treatment. Production and transport of chemicals for the purification process, as well as production of the electricity used, are also included. In this study we do not study the use phase of by-products from the process such as use of biogas and sludge. The functional unit used in this project is 1 m³ of treated wastewater fulfilling the yearly average discharge criteria specified in Table 1.

To quantify the potential environmental impact from processes, a number of environmental impact categories were selected, developed by CML (Centrum voor Milieukunde –Universiteit

Leiden, 2002) and within LCA general and common use (Guinée et al., 2002). However, in this paper we focus on Global Warming Potential (GWP), i.e. Carbon Footprint.

The GWP unit has been normalized to the reference unit using characterization factors. Nitrous oxide is, for example, normalized to carbon dioxide equivalents by multiplying the amount of nitrous oxide emissions by a factor of 298, as nitrous oxide has a 298 times stronger impact on global warming compared with carbon dioxide, per kg of emissions of each gas (in a 100-year perspective), (CML 2002).

Input data to the LCA related to the operation of the WWTP was retrieved from the process model and includes direct emissions, energy and chemical consumption, see Figure 3. Production data on coagulants and polymers used in the process were given from INCOPA (INCOPA, 2014). The sludge handling after the digester is not considered in this study, only amounts produced and emissions from short term storage at the WWTP are included.

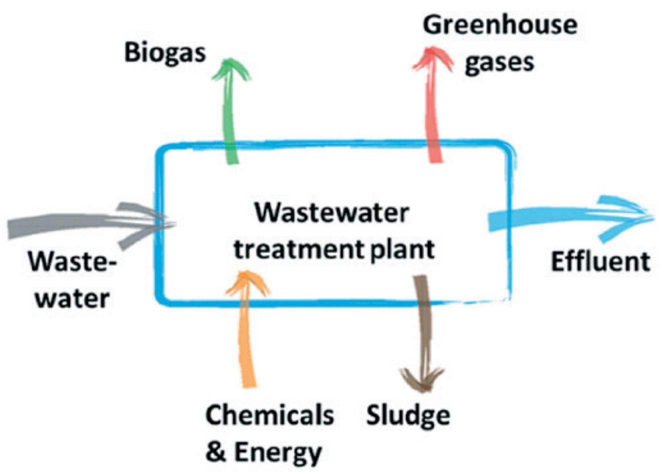

Figure 3: Illustration of inputs and outputs from the WWTP that drives the LCA. Note that sludge amounts only are considered and not any further handling of this output.

Energy production were set to be European average electricity mix and data taken from the data bases in the LCA software.

To study the effect of how different choices in the LCA impacts the result, a sensitivity analysis can be performed. In this study following sensitivity analysis were chosen:

- Change of energy source for electricity production.
- Usage of biogas. What is the impact if biogas replaces natural gas in the energy system?

4. RESULTS

Simulation of the three different process configurations were performed and data utilized in the LCA for the following scenarios:

- Baseline: Effluent standards that fulfils the criteria given.
- Stricter: More stringent limits on phosphorus (0.3 mg P/l)

In Figure 4 the GWP is presented for the different process configurations and effluent criteria.

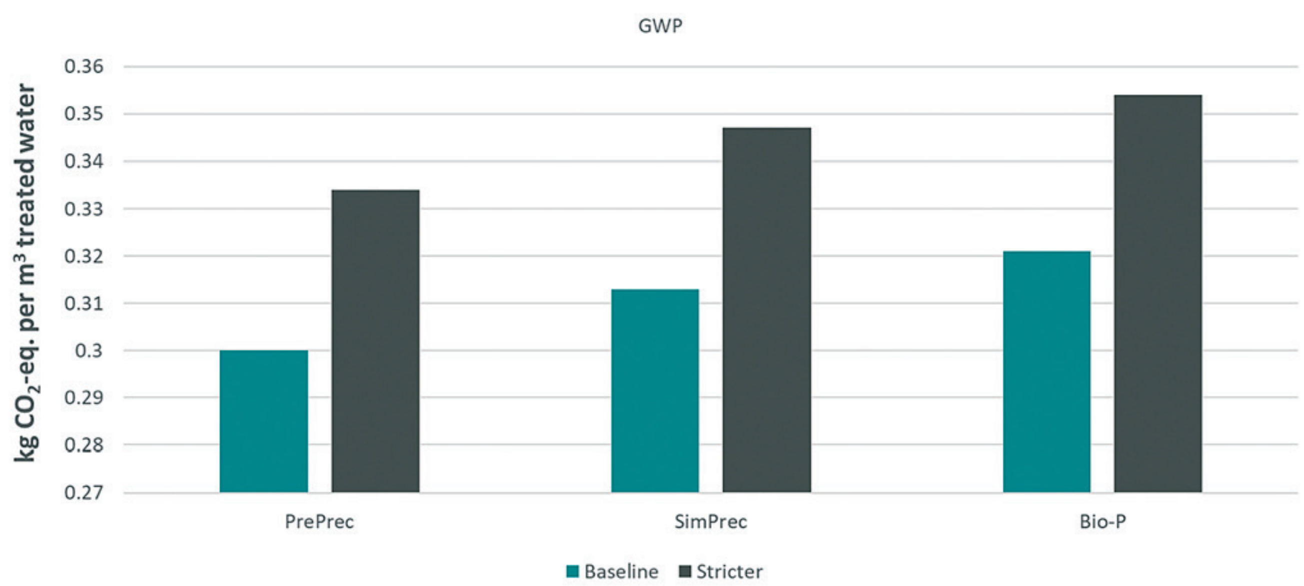

Figure 4: Global warming potential for the different process configurations. Results coloured according too effluent criteria. Note that the usage of biogas is included in these results.

When comparing the configurations, pre-precipitation gives the lowest GWP for both effluent scenarios. This is because the pre-precipitation configuration has the lowest load on the biological treatment and hence less energy is needed in this treatment step. Biological phosphorus removal has the highest GWP of the three configurations.

A more stringent effluent limit on phosphorus cause an increase of the GWP for all three process configurations. To fulfil the stricter limits on phosphorus there is a need for more coagulant. But that only explains a small share of the difference. Most of the additional GWP originates from the sand filter that is used in the post precipitation step that is included in all process configurations with the stricter effluent criteria. Sand filters has a fairly high energy usage that contributes to the global warming potential.

To see what affects to the GWP the figures are broken down into different resources needed and direct emissions from contributing process steps. As an example, the different contributions to GWP for the pre-precipitation step is shown in Figure 5.

The two main contributors to GWP are the electricity usage and the direct emissions of nitrous oxide (laughing gas) from the biological treatment. From the digester, slip of methane contributes to the GWP. Direct emissions of methane and nitrous oxide from sludge storage are the third largest contributor to GWP. The increased dosage of chemicals in the stricter effluent criteria does not affect the GWP in any significant way. The difference is mainly from the increased energy demand by introduction of a sand filter as a final polishing treatment step. Transportation of chemicals has the least contribution to the GWP.

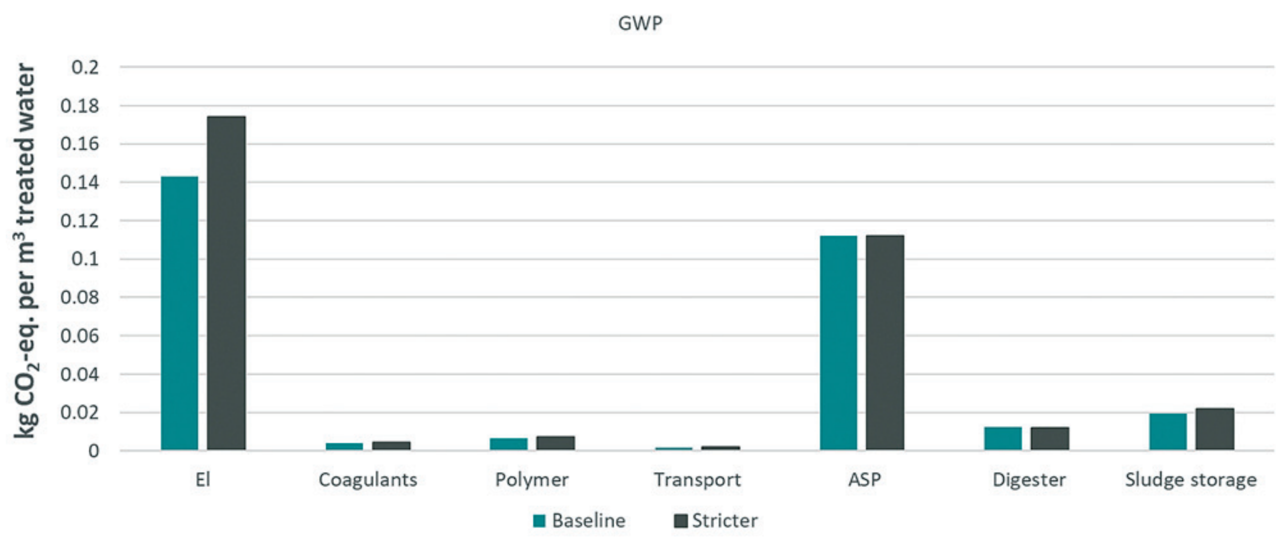

Figure 5: Contribution to the GWP for the pre-precipitation configuration. Results colored according too effluent criteria. Note that the usage of biogas is not included. El = electricity usage, ASP=Activated Sludge Process (release of N_2O in biological treatment).

The energy demand and biogas produced is compared for the different process configurations and effluent criteria. This is shown in Figure 6. The pre-precipitation produces more biogas than the other configurations since more primary sludge is produced and primary sludge generates more biogas secondary (biological sludge).

In Figure 7 the result of this credit of biogas is shown for the GWP of the process configurations. In the scenarios presented above, the biogas were not utilized in any way but most WWTPs use the as an energy source locally at the plant or upgrade it to for instance, vehicle fuel. In both the given examples biogas could replace fossil fuels as energy carrier. In this case biogas replace natural gas. This credit reduce the total contribution to the GWP by 20 to 30 % where pre-precipitation gives the highest reductions.

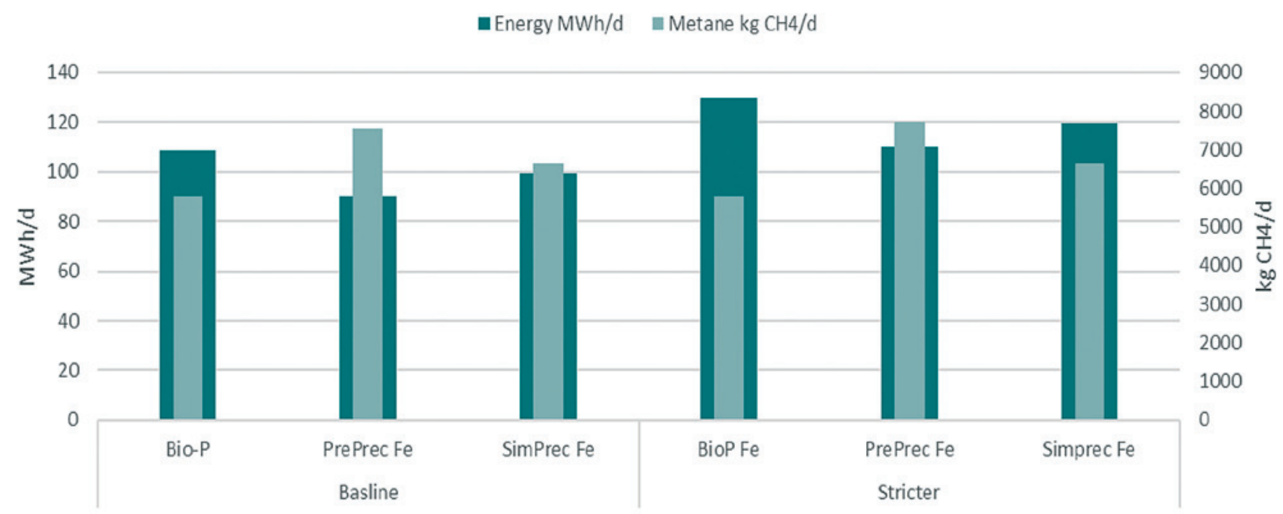

Figure 6: Comparison of energy demand (MWh/d) and biogas production (kg CH_4/d) for the different process configurations.

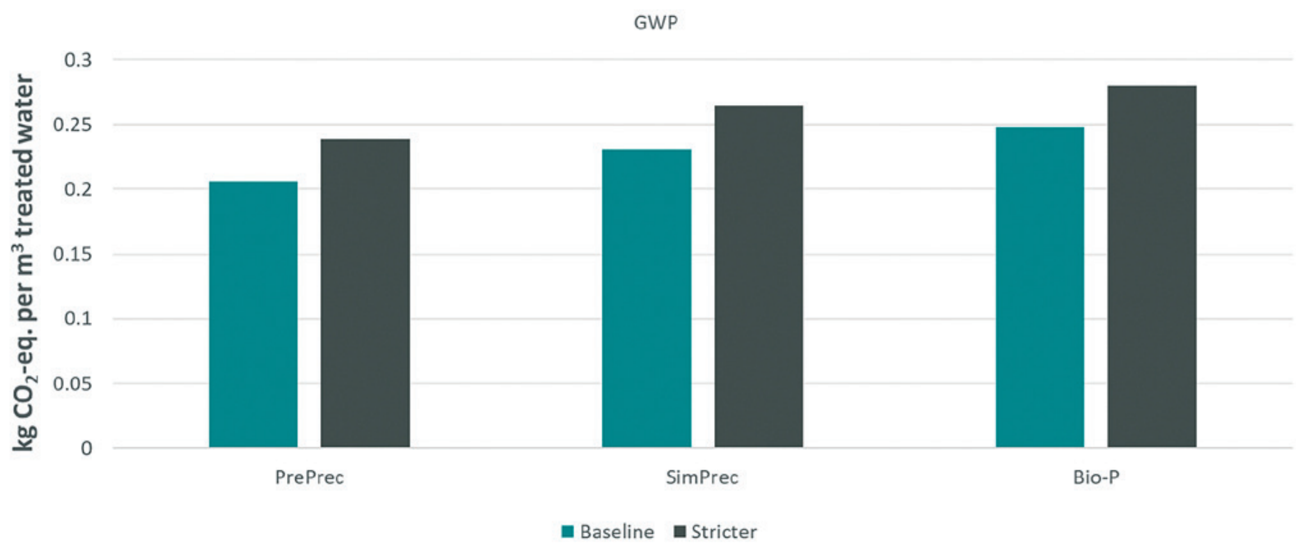

Figure 7: Contribution to the GWP after the biogas has replaced natural gas in energy production for the different process configurations. Results colored according too effluent criteria.

A sensitivity analysis was performed replacing the original European average electricity mix with 100 % hydropower reduced the total GWP of operating the process configuration with about 50 %.

5. CONCLUSIONS

Three process configurations for phosphorus removal from wastewater; pre-precipitation, simultaneous precipitation and biological phosphorus removal, was evaluated using dynamic process models and LCA.

Combining dynamic process models with life cycle assessment could give insight to what is large and not in the contribution to the global warming potential from different configurations of wastewater treatment plants. The use of models is a good method when real or test data are hard to retrieve from the process.

To conclude this study the main points are summarized below:

- Pre-precipitation clearly gives a lower GWP than the other configurations.
- Pre-precipitation produces the highest amounts of biogas while biological phosphorus removal produces the lowest amount of biogas.
- A more stringent effluent limit leads to a higher carbon footprint when sand filter is used in tertiary treatment.
- Choice of energy source is an important factor for the over-all Global Warming Potential.

6. DISCUSSIONS

Even though the chemicals has a low carbon footprint, an optimized use of chemistry on a WWTP can have a significant positive impact when used wisely. With Kemira KemConnect™ the dosage of chemicals are controlled in real-time and constantly kept on the level needed. Over and under dosage is avoided at the same time as treatment results are improved. More important, KemConnect can lower the environmental load in a variety of applications, i.e. KemConnect improves the WWTP's handprint by optimizing the treatment process and its results. Examples of KemConnect applications are:

- **KemConnect P** – Gives more stable phosphorus removal with the same or lower coagulant dosage.
- **KemConnect PT** –Finds the balance between pre-precipitation and biological treatment.
- **KemConnect SD** – Improves DS content and reject water quality in sludge dewatering.
- **KemConnect OCC** – Ensures low hydrogen sulphide levels in sewer systems and on WWTPs.

7. MISCELLANEOUS

More data and results from this study are found in LCA analysis of different WWTP processes, Rahmberg et al., 2020.

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