Swedish Environmental
Research Institute

Carbon footprint assessment of chemical and biological phosphorus removal

Effluent limits of phosphorus according to the updated Urban Wastewater Treatment Directive

Report number: U6957
Author: Kristin Johansson, Linnea Nilsson, Magnus Rahmberg

Commissioned by: INCOPA members Abwassertechnisches Beratungs- Und Serviceburo Jurgen Steding, Altair Chimica SpA, ALUCOM AG, Alumichem A/S, Archroma Management GmbH, Chemifloc Ltd, Chemische Fabrik Wocklum Gebr. Hertin GmbH & Co. KG, Chimica D'Agostino SpA, Clariant GmbH & Co. KG, Clinty Chemicals Ltd, Donau Chemie AG, EcoloChem Magyaróvár Kft, Feralco, Industrial Chemicals Ltd, Industrias Quimicas del Ebro SA – IQE, Kemcristal Srl, Kemira, Kronos International Inc, Kuhlmann Europe, Lubrico A. Tsakalis Ltd, Nobian, Precheza A.S., Química del Cinca SLU, Remondis Production GmbH, SAPEC Quimica SA, Sidra Wasserchemie GmbH, Società Chimica Bussi SpA, Trifer AG, Tronox, Venator, and Voda Nordic Oy.

March 2025

Summary

Wastewater treatment plants treat the influent wastewater with the objective to meet specified discharge criteria. In 2025, a revised Urban Wastewater Treatment Directive was approved, with the aim to improve the water quality through stricter water treatment. Many wastewater treatment plants will be affected by this revised directive, and the aim of this report is to compare the climate impact of different process configurations (biological and chemical phosphorus removal) fulfilling the requirements for phosphorus and nitrogen concentrations in the effluent according to the revised directive. An additional goal is to analyse whether chemical phosphorus removal can pose as an alternative to reach energy neutrality, in accordance with the revised directive.

The different process configurations were analysed through Life Cycle Assessment (LCA) with a focus on climate change, and the life cycle inventory data were generated through dynamic process simulations.

The main findings of this study are presented as following:

- Chemical phosphorus removal demonstrates a lower climate impact due to a lower electricity consumption and a higher biogas yield. Biogas is assumed to replace a fossil fuel, natural gas.
- Energy neutrality can be achieved to a greater extent by implementing chemical precipitation of phosphorus rather than biological removal. The main reason for this is the lower electricity consumption but also a higher biogas yield.
- Energy neutrality is more difficult to reach for the stricter effluent concentration of phosphorus (0.3 and 0.5 mg/l), primarily because a final polishing step is required (sand filter) which consumes energy.
- The climate impact increases when the effluent concentrations of phosphorus are stricter.
- The results in this study indicate that inorganic coagulants based on iron may have a lower climate impact than coagulants based on aluminium.

Table of contents

1 Introduction

In 2025, the revised Urban Wastewater Treatment Directive (UWWTD) (directive 2024/3019) was adopted by the European Union. The revised directive aims, among other things, to improve water quality and to address climate change through emission reductions. One measure of reducing avoidable greenhouse gas emissions is to achieve energy neutrality, where the national wastewater treatment sector shall aim to produce at least the same amount of energy required to operate the wastewater treatment processes.

By 2039, tertiary treatment (reduction of phosphorus and nitrogen) will be mandatory for wastewater treatment plants with a load of 150 000 person equivalents (PE) and above. To meet the stricter requirements for phosphorus in the effluent, different wastewater treatment process configurations can be implemented.

The aim of this study is to evaluate chemical phosphorus removal in wastewater treatment plants through a climate perspective. The aim is also to analyse whether chemical phosphorus removal can pose as an alternative to reach energy neutrality, in accordance with the revised UWWTD.

Dynamic process models can be used to evaluate different process configurations as they can be simulated to operate the same flow of incoming wastewater and the same load. The same process configurations were evaluated in Rahmberg et al. (2020), but they have been updated in this study based on the requirements in the revised UWWTD.

The report is structured accordingly: the methodology is presented in chapter 2, the scope of the LCA is presented in chapter 3, the results and their interpretation are presented in chapter 4, a discussion in chapter 5, and conclusions in chapter 6. References are presented last of all.

2 Methodology

2.1 Process modelling

This study utilizes the same models as presented in Rahmberg et al. (2020). The effluent discharge criteria for total phosphorus have been extended to also include the new criteria according to the revised UWWTD (2024/3019): 0.5 and 0.7 mg/l. In addition, two more phosphorus levels are included: 1.0 and 0.3 mg/l, where the latter is a limit value already implemented at many wastewater treatment plants in northern Europe.

This study also includes two more types of coagulants: ferric sulphate and PAC, but also includes ferric chloride and aluminium sulphate as per the 2020 report. The table below presents all the scenarios included in this study.

Table 1. A list of studied scenarios.

Process configuration	P_{tot} conc. in effluent	Type of coagulant
• Pre-precipitation • Simultaneous precipitation • Bio-P	• 0.3 mg/l • 0.5 mg/l • 0.7 mg/l • 1.0 mg/l	• Ferric chloride • Ferric sulphate • Aluminium sulphate • PAC

2.2 What is LCA and environmental footprints?

Life cycle assessment (LCA) investigates the environmental impacts related to a product or a system during its whole life cycle. This includes evaluating energy and resource consumption as well as emissions, from all life cycle stages including material production, manufacturing, use and maintenance, and end-of-life.

While LCAs generally cover many different environmental aspects (for example: climate change, eutrophication, toxicity, and water scarcity to mention a few), environmental footprints cover only one environmental aspect although still from a life cycle perspective. A carbon footprint hence covers the impact of climate change.

LCA is a widely used and accepted method for studies of environmental performance of various products and systems. The carbon footprint in this report is to a large extent performed in accordance with ISO 14040:2006 and ISO 14044:2006 standards. The results of this study have not been subject to a third-party review, as recommended by the previously mentioned standards.

3 Goal and scope of the LCA

3.1 Goal

The aim of this study is to quantify and analyse the carbon footprints of different wastewater treatment configurations based on the required effluent limits of phosphorus, according to the revised UWWTD (2024/3019).

A second goal is to compare different process configurations and the use of different inorganic coagulants with regards to their carbon footprints.

Finally, an additional goal is to explore the potential of achieving energy neutrality through biogas production.

3.2 System boundaries

The system boundaries of the LCA follows the same boundaries as the process models and the same treatment processes are included, however, the use of biogas is not modelled in the process simulations while it is in the LCA. In the figure below, a graphic representation of the system boundaries is presented.

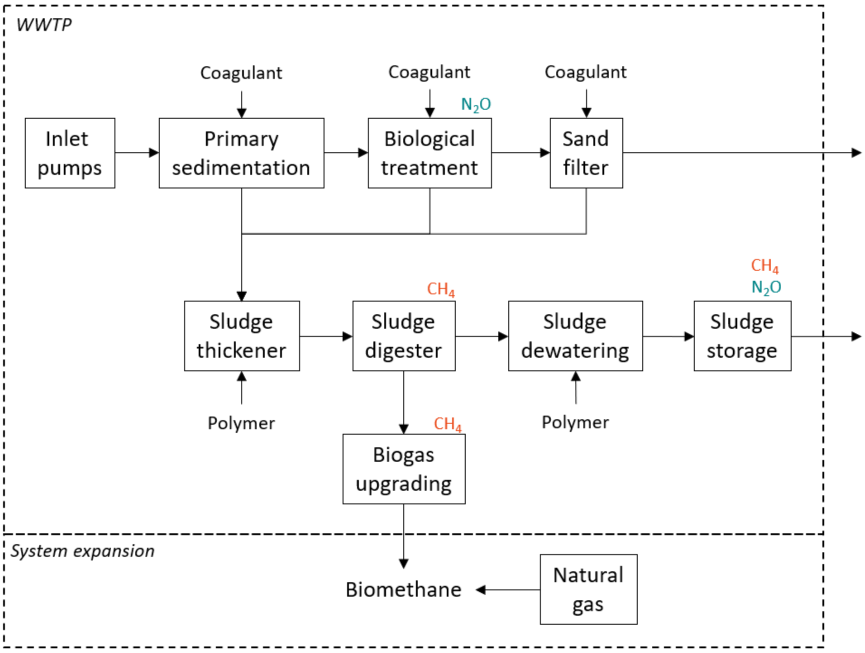

Figure 1. System boundaries of the LCA. The use of sewage sludge after storage is not included in the LCA.

The geographical scope of this study is Europe.

3.3 Functional unit

To be able to compare the function of different process configurations and different types of coagulants, the chosen functional unit is **1 m³ of treated wastewater**.

3.4 Impact assessment

This study focuses on the impact category **climate change**. Characterisation factors from IPCC AR6 (Intergovernmental Panel on Climate Change, Assessment Report 6) from 2021 is applied here to calculate the potential climate change.

3.5 Background data

The dynamic process models provide input data to the LCA model in terms of electricity use and consumption of chemicals, but the impacts from the production of electricity and chemicals are collected from LCA databases and reports. The carbon footprints of inorganic coagulants are taken from a recent study based on data from INCOPA member companies (Johansson & Liljenroth, 2023). Four types of coagulants have been included here, as specified below.

Table 2. A list of coagulants included in the process modelling and LCA modelling of wastewater treatment.

Coagulant	Production route or product type	Concentration of active substance % [Al] or [Fe]
Ferric chloride	Based on magnetite	13.8%
Ferric sulphate	Based on copperas	11.6%
Aluminium sulphate	Solid	9.0%
Polyaluminium chloride	PAC18	9.0%

Production of electricity is supplied as an average European grid mix to represent all wastewater treatment plants in the European region. The European grid mix is comprised of fossil fuels (40%), nuclear (25%) and renewables (35%).

Since this study does not look at a specific wastewater treatment plant in Europe, all transportation distances are set to 300 km by lorry. Transportation is relevant for chemicals used in the treatment plant, coagulants, and polymer.

3.6 Important assumptions

- Emission of nitrous oxide from the biological treatment is assumed to be 1% of incoming nitrogen to the plant, same assumption as in Rahmberg et al. (2020).

- Emission of methane from digesters and sludge treatment at the wastewater treatment plant is assumed to be 2.3% of produced biogas (Swedish Water and Wastewater association, 2024).

- Emissions from sludge storage (4 months) is assumed to be 2.9 kg methane per tonne of volatile solids, and for nitrous oxide 0.4% of total nitrogen in sludge, same assumption as in Rahmberg et al. (2020).

- All carbon in the influent is assumed to be of biogenic origin.

- Biomethane is assumed to replace the production and combustion of a fossil fuel (natural gas).

4 Results

The results of the study are presented in this chapter. As a general rule, the figures are divided into seven categories describing the climate impact from different inputs and outputs of the wastewater treatment process: production of electricity, production of inorganic coagulant, production of polymer, emissions from transports, emission of methane from the treatment process, emission of nitrous oxide from the treatment process and the avoided production of natural gas (assuming that biomethane can replace a fossil component on the market).

As another general rule, ferric chloride is used as an example in most figures, however this study also covers other inorganic coagulants. With regards to effluent emission limits of total phosphorus, most of the focus is kept on limits 0.5 and 0.7 mg/l since they are included in the revised UWWTD.

4.1 Comparing process configurations

In the figure below, carbon footprints for three different process configurations are presented: biological phosphorus removal, pre-precipitation and simultaneous precipitation using inorganic coagulants (ferric chloride, as an example here).

According to the figure below, the results indicate that pre-precipitation of phosphorus has a lower climate impact than the others, primarily due to a lower electricity consumption and a higher biogas production (resulting in a higher rate of avoided natural gas production). Less electricity is consumed due to that less organic matter needs to be aerated in the biological treatment step.

To reach the emission levels of phosphorus at 0.5 mg/l and lower a final polishing step is required for all process configurations. In this study, it is assumed to be a conventional sand filter. This has an impact on the electricity consumption, and the pumping required for backflushing of the filter corresponds to roughly 20% of the total energy consumption in the wastewater treatment process.

No external carbon source was added in the process models. Depending on the wastewater characteristics, this might be relevant for some plants.

Biological phosphorus removal has a higher electricity consumption since the bio-P process requires more recirculation pumping. Less sludge is produced resulting in a lower biogas yield.

In the process simulation performed in this study, low amounts of coagulant are still needed for the bio-P process to reach the stricter limits of phosphorus in the effluent: 0.3, 0.5, but also 0.7 mg/l. The consumption of coagulant in the bio-P case is barely visible in the figure below.

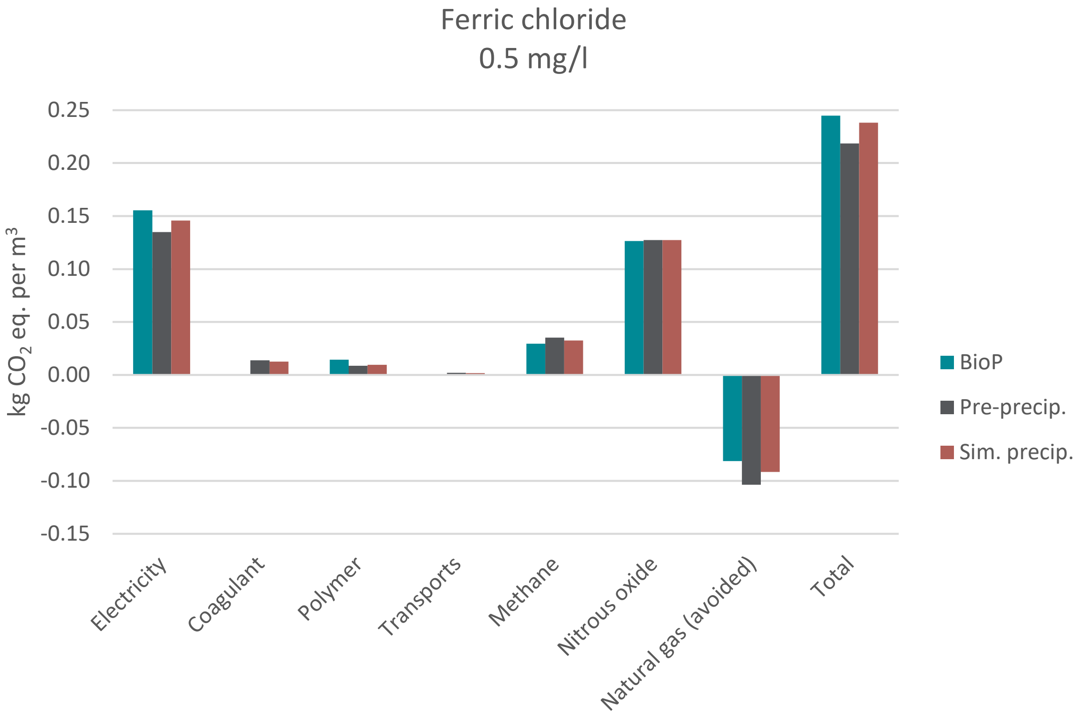

Figure 2. Carbon footprints of three different wastewater treatment processes. The results are expressed as kg of carbon dioxide equivalents per m³ of treated wastewater.

4.2 Impact of using different coagulants

In the figure below, carbon footprints for two different process configurations are presented: biological phosphorus removal and pre-precipitation using four different types of inorganic coagulants: ferric chloride, aluminium sulphate, ferric sulphate, and polyaluminium chloride (PAC).

According to the figure below, looking more specifically at the category “coagulant”, the results indicate that iron-based coagulants have a slightly lower climate impact than aluminium-based coagulants. This result was also present in Johansson & Liljenroth (2023) and the carbon footprints of the coagulants in this study were also based on that report. The relative contribution from the coagulants is still low independent on whether iron or aluminium is used, and compared to the biological phosphorus removal process the overall climate impact is lower for chemical pre-precipitation.

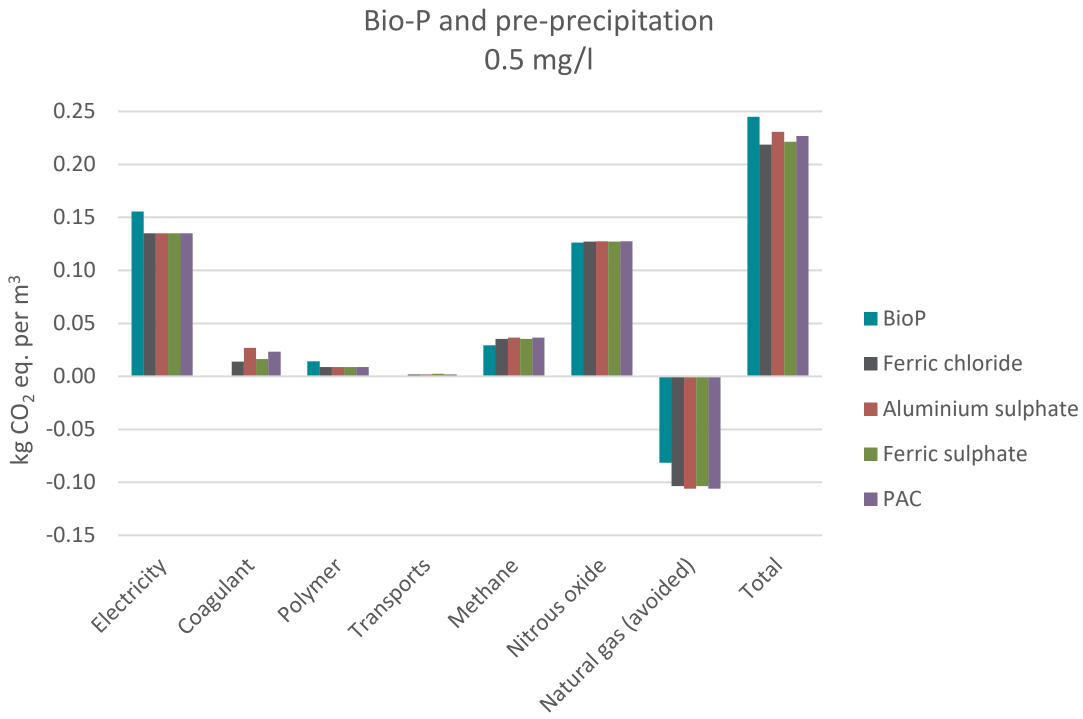

Figure 3. Carbon footprints of two different wastewater treatment processes and four types of inorganic coagulants for the effluent emission limit 0.5 mg/l of total phosphorus. The results are expressed as kg of carbon dioxide equivalents per m³ of treated wastewater.

4.3 Alternating the effluent emission limit of phosphorus

In the figure below, carbon footprints for four different effluent emission limits of total phosphorus are presented. The model is based on using ferric chloride as a coagulant in a pre-precipitation process.

According to the figure below, the results indicate that the climate impact is lower for less strict effluent emission limits of phosphorus. The primary reason for this is the use of sand filters which is required to reach the strict limits of phosphorus, but not required for the emission limits 0.7 and 1.0 mg/l total phosphorus. Sand filters require energy for pumping and backflushing, thus resulting in a higher carbon footprint.

The amount of coagulant used in the treatment process is similar between the different cases. This is due to the sand filter as well: the use of coagulants in the final polishing step is more efficient for removing phosphorus than applying it in the primary sedimentation. Not all phosphorus is available for the coagulant in this first sedimentation step.

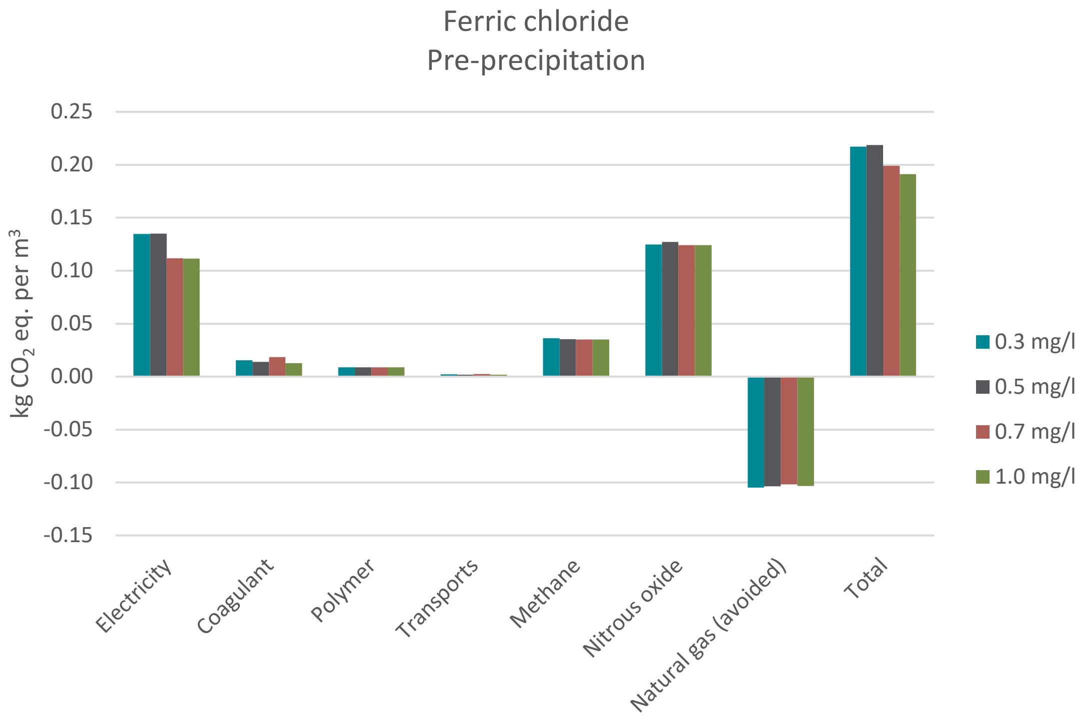

Figure 4. Carbon footprints of four different effluent emission limits of total phosphorus. The results are expressed as kg of carbon dioxide equivalents per m³ of treated wastewater.

4.4 What are the biggest contributions to the carbon footprint?

In the figure below, the carbon footprint of one scenario is presented: pre-precipitation using ferric chloride to achieve an effluent emission limit of phosphorus of 0.5 mg/l. The categories on the horizontal axis are divided into the individual processes of the wastewater treatment plant.

According to the figure below, the results indicate that it is the biological treatment step which has the highest climate impact. The main reason for this is the nitrous oxide emission which is a strong greenhouse gas. In this study, the nitrous oxide emission factor is based on an estimated value and considers the amount of incoming nitrogen to the wastewater treatment plant.

Another important step in the wastewater treatment plant is the assumption that biomethane can replace a fossil component (natural gas) which gives the treatment process a large, avoided emission (on the negative scale in the figure below). If the biogas was used in other applications, e.g., combusted in a combined heat and power plant, the avoided emissions could look differently depending on the available energy and heat provision in the region.

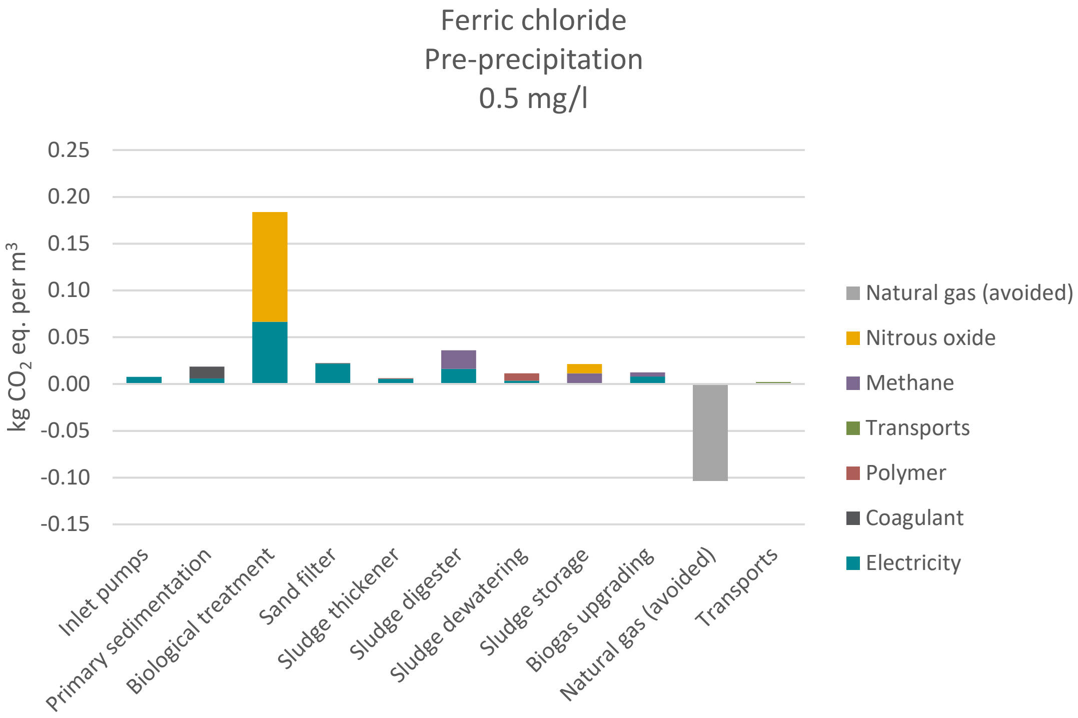

Figure 5. Carbon footprint of one type of process configuration, divided into the core processes. The results are expressed as kg of carbon dioxide equivalents per m³ of treated wastewater.

4.5 Sensitivity analysis

4.5.1 0.5 mg/l total phosphorus without using a sand filter

With the new urban wastewater treatment directive (Directive 2024/3019) as background, many large wastewater treatment plants in Europe will face stricter effluent emission limits of phosphorus. Plants with a capacity bigger than 150 000 p.e. will be required to achieve effluent phosphorus concentrations of 0.5 mg/l, while smaller plants will need to achieve 0.7 mg/l with regards to total phosphorus. Since some wastewater plants in Europe are not constructed with polishing steps like a sand filter already in place, a sensitivity analysis is performed to evaluate a scenario where no sand filter is used for the stricter phosphorus emission limit according to the new UWWTD.

With the current model setup, according to the simulation it was **not possible to reach a phosphorus concentration in the effluent of 0.5 mg/l**. There could be several reasons for this, for instance:

- The retention time in the sedimentation is not long enough to mix the coagulant well enough,
- Parts of the phosphorus is bound to small particles which do not sediment or bind to the coagulant,
- The coagulant used here (ferric chloride) could be changed to another type.

According to the figure below, the results indicate that the electricity “savings” by not using a sand filter is made up for by adding more coagulant. It is important to consider here that the scenario without a sand filter does not reach the same phosphorus concentration in the effluent, and that more inputs could be added to reach the correct limit value. If an additional type of coagulant is added, e.g., an aluminium based coagulant, the climate impact would increase for the scenario without a sand filter.

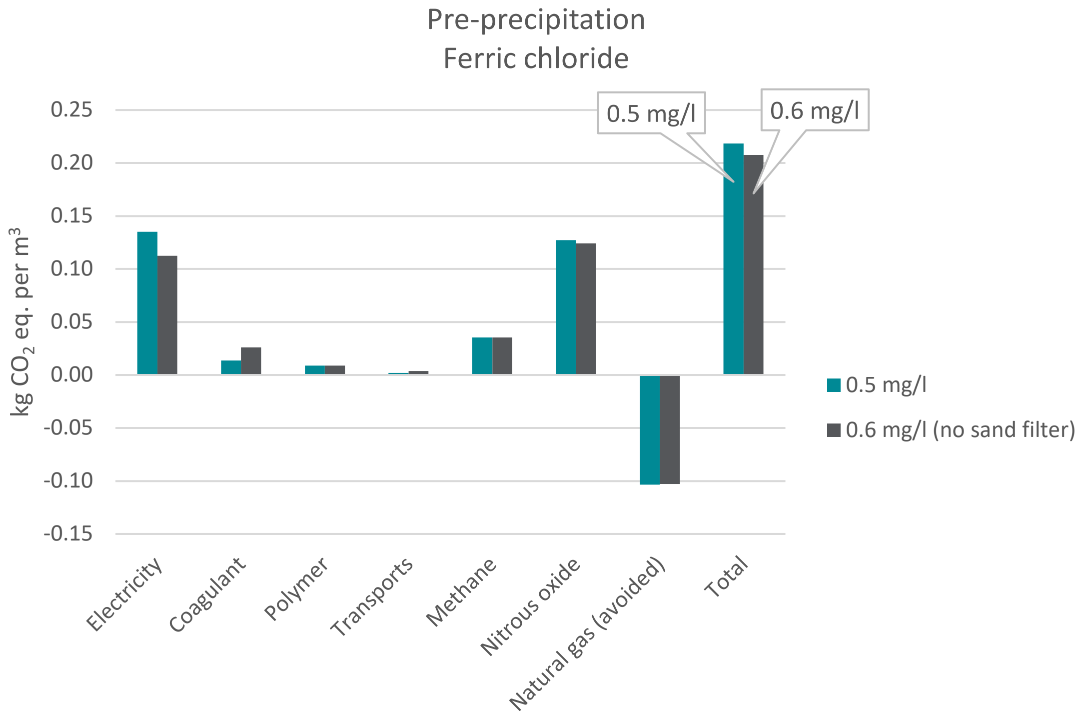

Figure 6. Carbon footprints of two process configurations: pre-precipitation with and without a sand filter. The results are expressed as kg of carbon dioxide equivalents per m³ of treated wastewater.

4.5.2 Using renewable electricity

In LCAs there are different ways to account for the environmental impact of the electricity supply. Two common ways to account for the impact from electricity production is to use a location-based approach or a market-based approach (as in the GHG Protocol). While the location-based approach considers the geographical area of the system under study, the market-based approach considers financial flows of electricity. Normally for an entity this can mean certificated electricity generated or purchased via different contractual instruments.

In this study, a location-based approach is used, and the geographical scope of this study is Europe. This assumption is tested in a sensitivity analysis where a market-based electricity mix is used instead. In this analysis it is assumed that a wastewater treatment organisation purchases renewable electricity (100% wind power) through financial instruments.

According to the figure below, the results indicate that the differences in climate impact between the different process configurations are less obvious than if an average European grid mix is applied in the LCA model. The only differences between the process configurations stems from the use of coagulant, polymer, methane emissions and the amount of produced biomethane.

Measures such as energy efficiency and energy use are less relevant from a climate perspective depending on how you model the electricity production. If a water utility purchases renewable electricity through financial instruments, it is important to also present an alternative view of the electricity impacts, such as a location-based perspective.

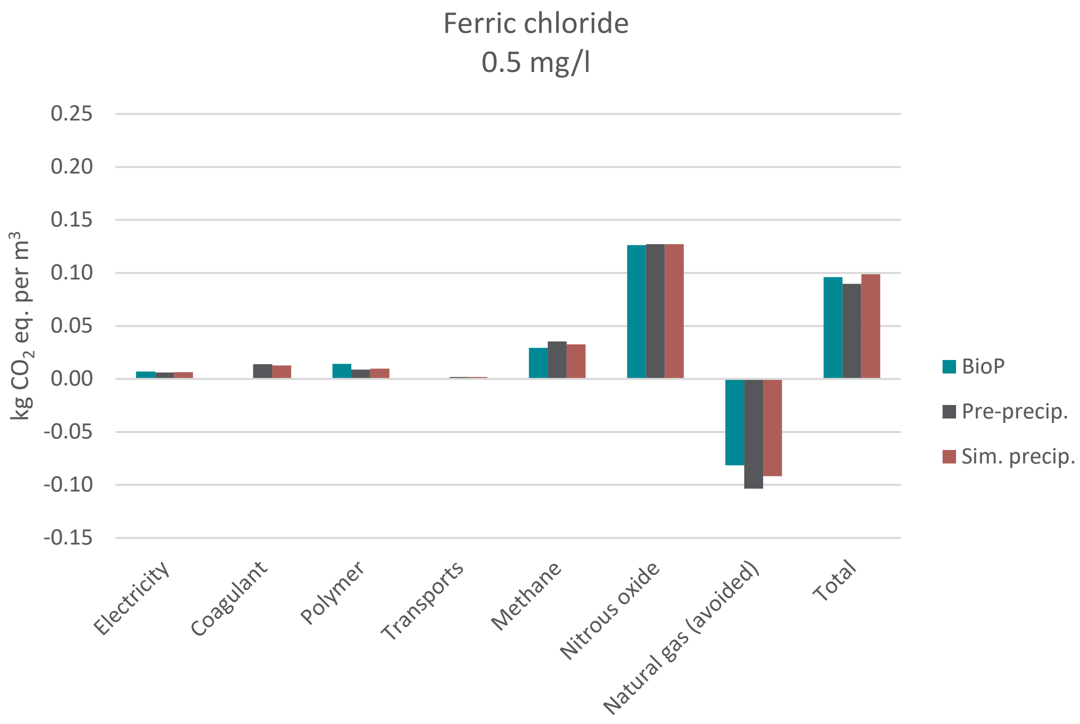

Figure 7. Carbon footprints of three process configurations (see chapter 4.1) but the electricity production is modelled as 100% renewable. The results are expressed as kg of carbon dioxide equivalents per m³ of treated wastewater.

4.6 Energy neutrality

According to the revised UWWTD (2024/3019) water utilities shall achieve energy neutrality on a national level with the aim of reducing avoidable greenhouse gas emission in the wastewater treatment sector. The directive states that the total annual energy generated on- or off-site by or on behalf of the plant operators shall be equivalent to at least 100% of the total annual energy used by plants by 2045.

The energy neutrality demand is relevant for plants treating the load of 10 000 p.e. and above, and in between now and the year 2045 there are stepwise goals to achieve energy neutrality in parts.

In this study, we wanted to compare the energy neutrality potential of different process configurations and phosphorus concentrations in the effluent. In reality, the energy neutrality goal should be met on a national level, and not for each individual m^3 of treated wastewater, so these results should be used as an indication rather than a rule.

The directive has not specified an exact calculation guideline for the energy neutrality at the time of publication of this report. To calculate the energy neutrality ratio for each process configuration, this formula is used:

$$\frac{Amount\ of\ produced\ biogas\ (MJ)}{Sum\ of\ electricity\ used\ (MJ)} = Energy\ neutrality\ ratio$$

According to the table below, the results indicate that the biological phosphorus removal process performs worst with regards to energy neutrality, while the pre-precipitation process performs the best. The main reason for this is the higher biogas yield. There is also a notable difference between the stricter and less strict phosphorus limits with regards to energy neutrality, and that is the energy consumption of the final polishing step necessary to meet the stricter phosphorus limits (sand filter).

Table 3. Energy neutrality results for different process configurations. The values in the table header are the phosphorus concentration in the effluent. A result of 100% indicates that the treated m^3 of wastewater is energy neutral.

Process configuration	0.3 mg/l	0.5 mg/l	0.7 mg/l	1.0 mg/l
Bio-P	60%	60%	60%	63%
Pre-precipitation	89%	88%	105%	106%
Sim. precipitation	72%	72%	84%	84%

Also worth noting is that these results are in fact a result from the process models and not based on the carbon footprint results. Energy is utilized in these calculations in terms of MJ or kWh rather than the climate impact from the electricity production.

The same system boundaries are applied as in the process models and LCA, meaning that sludge treatment is excluded as well as pumping stations located in the sewer systems.

Possible measures to increase the energy neutrality for wastewater plants could be to

- Increase the energy efficiency of the plant by optimizing processes,
- Produce more biogas through digestion of sewage sludge,
- Utilize waste heat sources,
- Invest in photovoltaics or wind power plants,
- Lower the temperatures,
- Recover heat from sewer systems,
- Recover energy from sewage sludge.

5 Discussion

This study utilizes the same models as in Rahmberg et al. (2020) but they have been updated with regards to the phosphorus concentrations in the effluent to match the new requirements described in the UWWTD. In the figure below, a comparison between the two studies have been made. The scenario depicted is pre-precipitation using ferric chloride and with a phosphorus concentration in the effluent of 0.3 mg/l, since it was included in both studies.

According to the figure below, it is the climate impact of electricity production which has changed the most. This is not because the electricity consumption at the wastewater plant has decreased, but rather the electricity production in Europe which has lowered its climate impact. The climate impact from methane and nitrous oxide emissions have increased slightly, which is due to the update of characterization factors from IPCC since the last study. The production of coagulant has slightly increased since new data on the production of coagulants was published two years ago (Johansson & Liljenroth, 2023).

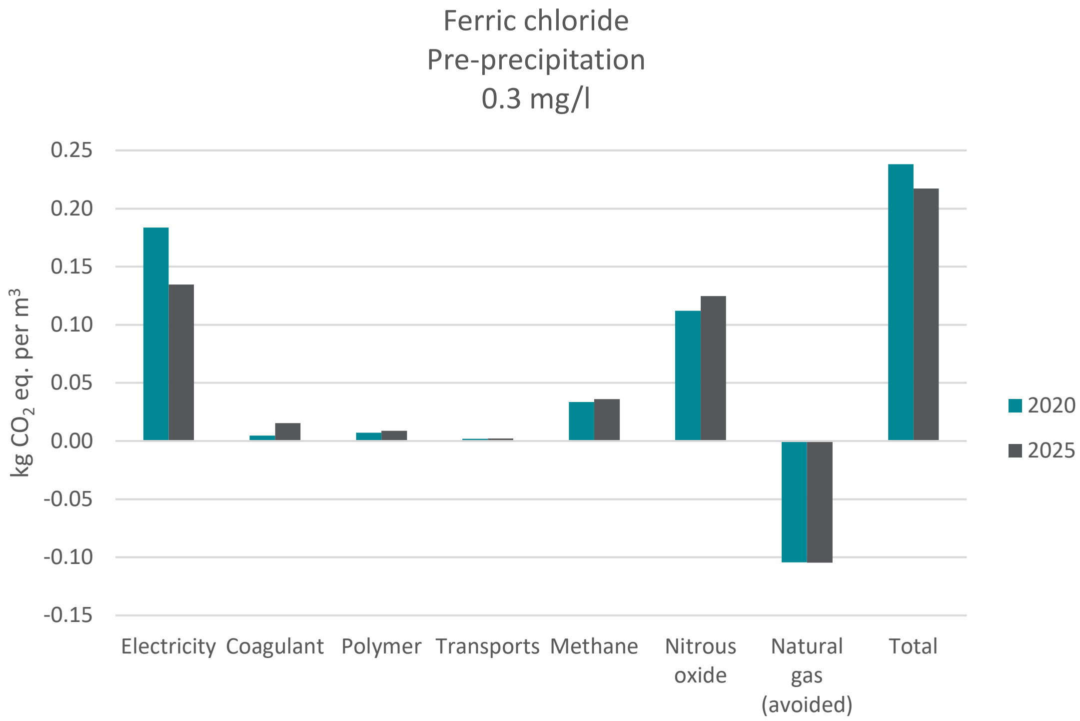

Figure 8. Comparison of the carbon footprint results published in this study The results are expressed as kg of carbon dioxide equivalents per m^3 of treated wastewater.

As mentioned in chapter 4.5.1, it was not possible to reach the limit of 0.5 mg/l of total phosphorus in the effluent without using a sand filter as a final polishing step. However, it might be possible to reach 0.5 mg/l without using a sand filter if, for example, the sedimentation process is optimized, or if the characteristics of the incoming water are different from the incoming water defined in this study.

In the table below, a hypothetical result for the energy neutrality assessment is presented. In this scenario we assume that the energy consumption for the sand filter is excluded for the phosphorus concentration of 0.5 mg/l in the effluent with the aim of seeing how the energy neutrality ratio is affected. If water utilities can reach 0.5 mg/l without using a sand filter the resulting energy neutrality ratio is improved, however, these results do not consider the potential impact on climate change: if we need to add more coagulants to reach the limit it is not certain the carbon footprint is improved. This table should be used as an indication rather than as a result from the model simulation.

Table 4. A hypothetical result for the energy neutrality comparison (see Table 3 above) where we assume that a sand filter is not necessary to reach the effluent phosphorus limit of 0.5 mg/l. This assumption is made for all process configurations. A result of 100% indicates that the treated m³ of wastewater is energy neutral.

Process configuration	0.3 mg/l	0.5 mg/l	0.7 mg/l	1.0 mg/l
Bio-P	60%	70%	70%	63%
Pre-precipitation	89%	105%	105%	106%
Sim. precipitation	72%	85%	84%	84%

In a recent study from 2024, Högstrand et al. also performed an LCA of biological and chemical phosphorus removal based on life cycle inventory data retrieved from dynamic process simulation (a similar method as in this study). The study also concluded that biological phosphorus removal had a higher electricity consumption and a lower biogas yield than chemical precipitation, but the main difference between the process configurations was the higher methane emissions from the bio-P setup.

Compared to the model in this study, the model made by Högstrand et al. is more complex and contains several more treatment steps: a side-stream hydrolysis, struvite precipitation, ozonation, an MBBR process, and disc filters. In this study, no water-line methane emissions were included (although sludge-line emissions were included), which might make a straight comparison between the studies difficult. Downstream sludge treatment was also included by the authors, but the climate impact was relatively small in comparison to the direct air emissions from the water treatment processes.

In conclusion, direct air emissions can vary to a large extent and therefore has a big impact on the climate footprint of wastewater treatment. The results from this study could be used as a guideline and it can be used to make more general conclusions regarding the choice of biological or chemical phosphorus removal in a European perspective.

6 Conclusions and recommendations

To conclude this study, the main conclusions are summarized below.

- The results indicate that biological phosphorus removal can have a higher carbon footprint than chemical precipitation. This is primarily due to a higher electricity consumption and a lower biogas yield.

- If the electricity grid mix changes in favour of a renewable electricity source, e.g. wind power, the resulting climate impact is very similar if we compare biological phosphorus removal to chemical precipitation of phosphorus.

- The choice of coagulant has a relatively small impact on the total carbon footprint of wastewater treatment. Iron-based coagulants can potentially have a lower climate impact than aluminium-based coagulants.

- The results in this study also indicate that stricter effluent limitations of phosphorus imply a higher carbon footprint.

- The choice of sand filter as a final step in the WWTP can have a relatively big influence on the results due to the electricity consumption for backflushing – other polishing steps could be evaluated as well.

- According to this study, energy neutrality could be easier to achieve by using chemical precipitation than biological phosphorus removal. Due to a lower electricity consumption and a higher biogas yield chemical precipitation is indicated to perform better with regards to the energy balance. This is independent of the choice of coagulant. More guidelines on how energy neutrality should be calculated are expected from the European Commission in the future.

7 Reference list

EU directive 2024/3019, 27 November 2024, concerning urban wastewater treatment.

Högstrand, S., Wärff, C., Svanström, M., Jönsson, K. (2024) Dynamic process simulation for life cycle inventory data acquisition – environmental assessment of biological and chemical phosphorus removal. Journal of cleaner production 479 (2024) 144047.

Johansson, K., Liljenroth, A. (2023) Carbon footprints of inorganic coagulants. IVL report U6780.

Rahmberg, M., Andersson, S. L., Lindblom, E. U., Johansson, K. (2020) LCA analysis of different WWTP processes. IVL report B2400.

Swedish Water and Wastewater association (2024). Klimatneutral VA-bransch. Available at: https://www.svensktvatten.se/vara-sakomraden/klimat-och-hallbarhet/klimatneutral-va/. Retrieved: 2025-02-06.

STOCKHOLM
Box 21060, 100 31 Stockholm

GOTHENBURG
Box 53021, 400 14 Gothenburg

MALMÖ
Nordenskiöldsgatan 24
211 19 Malmö

KRISTINEBERG
(Center for Marine Research and Innovation)
Kristineberg 566
451 78 Fiskebäckskil

SKELLEFTEÅ
Kanalgatan 59
931 32 Skellefteå

BEJING, CHINA
Room 612A
InterChina Commercial Building No.33
Dengshikou Dajie
Dongcheng District
Beijing 100006
China

This report has been reviewed and approved in accordance with IVL's audit and approval management system.