

Master's Programme in Water and Environmental Engineering

Integrating coagulation and granular activated carbon filtration at a Finnish wastewater treatment plant

Pilot-scale assessment of combined phosphorus and micropollutant removal

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Abstract

The revised Urban Wastewater Treatment Directive (EU 2024/3019) introduces mandatory requirements for micropollutant removal at large municipal wastewater treatment plants. A minimum of 80 % removal efficiency should be met for at least six indicator substances. Additionally, Helsinki Region Environmental Services Authority aims to reduce effluent total phosphorus to approximately 0.1 mg/L annual average, stricter than current environmental permit limits. Chemical coagulation combined with granular activated carbon (GAC) filtration offers a promising approach for simultaneous treatment, where GAC functions as a mechanical filtration stage for enhanced phosphorus removal after coagulation, while adsorbing micropollutants.

This study evaluated the combined process through laboratory- and pilot-scale experiments at Viikinmäki wastewater treatment plant. Two parallel pilot-scale GAC columns were operated for three months, one with polyaluminium chloride dosing and one without, enabling direct performance comparison. The 0.1 mg/L phosphorus target was consistently achieved at both laboratory- and pilot-scale tests, notably also without chemical dosing. The column with chemical dosing demonstrated enhanced phosphorus removal after initial stabilization, requiring a high molar ratio due to already low phosphorus concentrations in Viikinmäki effluent (below 0.2 mg/L). In addition to phosphorus removal, micropollutant removal exceeded 90 % for most EU Directive's indicator substances in both columns. Furthermore, hydraulic performance remained stable under chemical dosing despite GAC surface modifications, and residual aluminium in effluent remained consistently low.

The results demonstrate technical feasibility of meeting both micropollutant removal requirements and stringent phosphorus removal targets with the combined process. However, the limited three-month pilot campaign does not reflect long-term treatment performance and cannot evaluate GAC exhaustion.

Keywords GAC, enhanced phosphorus removal, micropollutants, wastewater

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Työn nimi Kemiallisen saostuksen ja rakeisen aktiivihiilisuodatuksen yhdistäminen suomalaisella jätevedenpuhdistamolla - Pilot-mittakaavan tutkimus fosforin ja haitta-aineiden poistosta

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Tiivistelmä

Uudistettu yhdyskuntajätevesidirektiivi (EU 2024/3019) tulee asettamaan haitta-aineiden poistovelvoitteita suurille yhdyskuntajätevedenpuhdistamoille. Vähintään 80 % poistoteho tulee saavuttaa ainakin kuudelle direktiivin indikaattoriaineelle. Lisäksi Helsingin seudun ympäristöpalvelut -kuntayhtymällä on tavoitteena pienentää vesistöön menevää fosforikuormaa ympäristölupaa tiukemmalle tasolle siten, että lähtevän veden kokonaisfosforipitoisuus olisi vuosikeskiarvona noin 0,1 mg/l. Kemiallinen saostus yhdistettynä rakeiseen aktiivihiileen (GAC) on lupaava fosforin ja haitta-aineiden poistomenetelmä, jossa GAC toimii saostuksen jälkeisenä mekaanisena suodatusvaiheena fosforin poistolle samalla adsorboiden haitta-aineita.

Tässä työssä arvioitiin yhdistettyä prosessia laboratorio- ja pilot-mittakaavan kokeilla Viikinmäen jätevedenpuhdistamolla. Pilotointi suoritettiin kahdella rinnakkaisella GAC-suodattimella, joista toinen toimi vertailulinjana ilman kemikalointia, ja toiseen syötettiin polyalumiinikloridia. Alle 0,1 mg/l kokonaisfosforipitoisuus saavutettiin sekä laboratorio- että pilot-mittakaavan kokeissa, pääosin myös ilman kemikaalin annostelua. Suodatin, johon syötettiin kemikaalia, osoitti tehokkaampaa fosforin poistoa alun tasapainoittumisen jälkeen. Saostus vaati kuitenkin korkean moolisuhteen Viikinmäen lähtevän veden jo valmiiksi alhaisen fosforipitoisuuden vuoksi (alle 0,2 mg/l). Fosforin poiston ohessa haitta-aineiden poistoteho ylitti 90 % suurimmalle osalle EU-direktiivin indikaattoriaineista molemmissa suodattimissa. Myös hydraulinen suorituskyky pysyi tasaisena kemikaaliannostelun aikana hiilen pintarakenteen muutoksista huolimatta, minkä lisäksi pilotilta lähtevä jäännösalmiini pysyi alhaisena.

Tulokset osoittavat yhdistetyn prosessin teknisen toteuttavuuden sekä haitta-aineiden poistovaatimusten että tiukkojen fosforin poistotavoitteiden osalta. Pilotointijakso oli kuitenkin rajattu kolmeen kuukauteen, joten tulokset eivät kuvasta pitkän aikavälin käsittelytehoa tai hiilen kyllästymistä.

Avainsanat GAC, fosforinpoiston tehostaminen, haitta-aineet, jätevesi

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Abbreviations

API	active pharmaceutical ingredient
BV	bed volume
DOC	dissolved organic carbon
EBCT	empty bed contact time
EDS	energy dispersive X-ray spectroscopy
EQS	environmental quality standards
FeCl ₃	ferric chloride
FeSO ₄	ferrous sulphate
GAC	granular activated carbon
HLR	hydraulic loading rate
HRT	hydraulic retention time
IBC	intermediate bulk container
ICP	inductively coupled plasma
LOQ	limit of quantification
MTZ	mass transfer zone
MS	mass spectrometry
OES	optical emission spectrometry
PAX	polyaluminium chloride
PAX-GAC	GAC column operated with PAX coagulation
PE	population equivalent
PO ₄ -P	orthophosphate
PVC	polyvinyl chloride
RSSCT	rapid small-scale column tests
SEM	scanning electron microscope
SMT	Standards, Measurement and Testing protocol
TP	total phosphorus
TSS	total suspended solids
TSP	total soluble phosphorus
UV ₂₅₄	UV absorbance at 254 nm
VFD	variable frequency drive
WFD	Water Framework Directive
WWTP	wastewater treatment plant

1 Introduction

Removal of nutrients and micropollutants represents a growing challenge for wastewater treatment plants (WWTPs) aiming to meet future discharge requirements. While phosphorus is an essential nutrient to all forms of life, its excessive discharge into aquatic environments leads to eutrophication. Similarly, organic micropollutants include a wide range of trace contaminants such as pharmaceuticals, personal care products and pesticides that persist through conventional biological treatment systems and can adversely affect aquatic organisms even at very low concentrations (Baresel et al., 2019; Luo et al., 2014).

The revised Urban Wastewater Treatment Directive (EU 2024/3019) introduces mandatory requirements for micropollutant removal in addition to stringent nutrient removal limits. The directive requires an average removal efficiency of 80 % for at least six selected indicator substances at large WWTPs (>150 000 population equivalent, PE) and strengthens the total phosphorus (TP) discharge limit to 0.5 mg/L with 90 % removal efficiency (EU, 2024). However, Helsinki Region Environmental Services Authority (HSY) aims to reduce the effluent TP discharge to receiving waters beyond the EU directive and HSY's already stricter environmental permit limits, targeting an annual average effluent TP concentration of 0.1 mg/L. The enhanced phosphorus removal should be implemented by the time the micropollutant removal requirements become mandatory. Therefore, HSY initiated this pilot-scale study to investigate, whether these tightened requirements could be met within a combined process through chemical coagulation utilizing polyaluminium chloride (PAX) and granular activated carbon (GAC) adsorption.

GAC filtration is one of the most promising technologies for efficient micropollutant removal and has been successfully applied in Switzerland and Germany (Böhler et al., 2023; Wunderlin and Bitterwolf, 2025). GAC provides a large internal surface area for adsorption of dissolved organic compounds and is widely used for its efficiency and operational robustness (Çeçen and Aktaş, 2011; Worch, 2012). However, GAC exhibits very limited adsorption capacity for phosphorus removal, as phosphate ions are poorly adsorbed onto the carbon surface (Acosta et al., 2021). Therefore, GAC filtration can be combined with a chemical coagulation step for phosphorus removal, where metal salts, e.g. aluminium- or iron-based coagulants, form particulate phosphorus flocs that can be retained and removed within the GAC filter bed by backwashing (Altmann et al., 2016b). Consequently, GAC inherently functions as a mechanical filtration step for phosphorus removal, capable of retaining suspended solids and particulate phosphorus in its upper layers. The combined process therefore has the potential to fulfil both

nutrient and micropollutant removal requirements in a single filtration step. Several pilot-scale studies have demonstrated the feasibility of this approach (Altmann et al., 2016b; Locher and Blind, 2024; Telgmann et al., 2020). However, the applicability of such combined systems remains unstudied under Finnish conditions and with ultra-low effluent TP concentrations. In addition, the impact of coagulation on GAC performance needs to be further studied.

This study was conducted in collaboration with HSY at Viikinmäki WWTP, which serves a PE of 1.2 million (HSY, 2025). The objective was to evaluate whether combined PAX coagulation and GAC filtration can achieve simultaneous removal of phosphorus and micropollutants under Finnish WWTP conditions. The research included laboratory-scale flocculation jar tests and column experiments to determine optimal PAX dose, followed by pilot-scale measurement campaign on combined phosphorus and micropollutant removal performance.

The primary research question was defined as:

- Can simultaneous removal of phosphorus and micropollutants be achieved through combined PAX coagulation and GAC filtration at Viikinmäki WWTP?

To address this question, the following subordinate questions were set:

- What is the optimal PAX dose and Al:PO₄-P molar ratio required to achieve efficient phosphorus removal and reach effluent concentrations of 0.1 mg/L TP?
- How does PAX dosing influence the hydraulic performance of the GAC column?
- Does aluminium accumulate in the filter media, and what is the residual aluminium concentration in the GAC filter effluent?
- How does PAX dosing influence the micropollutant adsorption capacity of the GAC filter, and can UV absorbance at 254 nm (UV₂₅₄) be used as a surrogate parameter for monitoring micropollutant removal efficiency in the combined process?

The scope of this thesis is limited to the quaternary treatment of municipal WWTP effluent using aluminium-based coagulant and coal-based regenerated GAC media. Alternative coagulants or GAC materials, as well as long-term GAC breakthrough behaviour are excluded from this study. The study focuses on short-term process performance and operational feasibility during both laboratory- and pilot-scale measurement campaigns conducted in summer 2025 at Viikinmäki WWTP.

The structure of the thesis is as follows: Chapter 2 provides a literature review covering the regulatory framework, fundamentals of GAC adsorption and chemical phosphorus removal, and previous studies on combined processes. Chapter 3 presents the experimental setup, materials and analytical methods. Chapter 4 shows the results from laboratory- and pilot-scale experiments, followed by discussion in Chapter 5. Conclusions are summarized in Chapter 6.

2 Literature review

This chapter presents the theoretical background and previous studies relevant to combined phosphorus and micropollutant removal using chemical coagulation and GAC filtration. The chapter first reviews the regulatory framework that establishes the requirements for this study (Section 2.1). After this, the fundamentals of GAC adsorption and its application in wastewater treatment are presented (Section 2.2), followed by the principles of chemical phosphorus removal (Section 2.3). Finally, previous pilot-scale studies on combined coagulation and GAC filtration are reviewed (Section 2.4).

2.1 Regulatory framework

The regulatory framework for this study is established by EU and Finnish legislation. This section first presents the revised Urban Wastewater Treatment Directive, which introduces mandatory micropollutant removal requirements (Section 2.1.1). The Finnish regulatory context and Viikinmäki WWTP's targets are then discussed (Section 2.1.2).

2.1.1 Urban Wastewater Treatment Directive

The European Union published the revised Urban Wastewater Treatment Directive (EU 2024/3019) in December 2024. A notable addition in the revised directive is the introduction of mandatory micropollutant removal requirements for municipal wastewater treatment plants. In this context, micropollutants are defined as trace-level contaminants such as pharmaceuticals and pesticides that persist through conventional biological treatment processes. Previously, the EU only set requirements to monitor these substances without setting removal requirements. The requirement for micropollutant removal applies to WWTPs serving more than 150 000 PE, or plants above 10 000 PE in areas sensitive to micropollutant pollution (EU, 2024). The directive establishes a phased implementation schedule for micropollutant removal. For plants above 150 000 PE, 20 % of wastewater from these plants must meet micropollutant removal requirements by the end of 2033, 60 % by the end of 2039, and 100 % of these plants by the end of 2045 (EU, 2024).

The directive specifies a minimum removal efficiency of 80 % for selected organic micropollutants, measured using specific indicator substances. The directive lists 12 indicator substances divided into two categories: substances that can be very easily treated (Category 1) and substances that can be easily removed (Category 2). The indicator substances are listed in Table 1.

Treatment plants must achieve 80 % removal for at least six substances from the list, of which at least four of the compounds must be selected from Category 1 and two from Category 2. If less than six substances can be measured at sufficient concentrations, competent authorities may designate alternative substances. The directive specifies that removal efficiency must be calculated using the arithmetic mean of individual substance removal rates, which allows individual removals below 80 % as long as the overall average meets the requirement. Samples should be collected from the influent and effluent using 48-hour composite samples under dry-weather conditions. For large plants (>150 000 PE), sampling should be conducted twice a month (EU, 2024).

Table 1. List of EU 2024/3019 indicator substances for micropollutant removal.

Indicators	Minimum % of removal in relation to the influent load
Substances that can pollute water even at low concentrations (see Note 1)	80 % (see Note 2)
Category 1 (substances that can be very easily treated)	Category 2 (substances that can be easily disposed of)
(i) Amisulpride (CAS No 71675-85-9) (ii) Carbamazepine (CAS No 298-46-4) (iii) Citalopram (CAS No 59729-33-8) (iv) Clarithromycin (CAS No 81103-11-9) (v) Diclofenac (CAS No 15307-86-5) (vi) Hydrochlorothiazide (CAS No 58-93-5) (vii) Metoprolol (CAS No 37350-58-6) (viii) Venlafaxine (CAS No 93413-69-5)	(i) Benzotriazole (CAS No 95-14-7) (ii) Candesartan (CAS No 139481-59-7) (iii) Irbesartan (CAS No 138402-11-6) (iv) Mixture of 4-Methylbenzotriazole (CAS No 29878-31-7) and 5-methylbenzotriazole (CAS No 136-86-6)
Note 1: The concentration of the organic substances in Category 1 and 2 must be measured.	
Note 2: The removal percentage must be calculated on dry weather flow for at least 6 substances. The number of substances in Category 1 must be twice the number of substances in Category 2. If less than 6 substances can be measured in sufficient concentration, the competent authority shall designate other substances to calculate the minimum % of removal, when necessary. The average of the specific removal of all individual substances used in the calculation must be applied to assess whether the required minimum removal of 80 % has been achieved.	

Beyond micropollutant removal, the directive includes changes to nutrient and total suspended solids (TSS) removal, as well as new requirements related to climate neutrality and monitoring of microplastics. With respect to

phosphorus, the directive strengthens the removal requirements for large WWTPs (>150 000 PE) to 0.5 mg/L TP with 90 % removal efficiency compared to previous requirements of 1.0 mg/L TP and 80 % removal. In addition, the directive expands monitoring obligations compared to the previous Directive 91/271/EEC.

2.1.2 National legislation in Finland and the Viikinmäki context

In Finland, WWTPs are currently regulated under Government Decree 1022/2006 on hazardous and harmful substances in aquatic environments. Decree 1022/2006 implements the EU Water Framework Directive's (WFD, 2000/60/EC) priority substances and nationally selected harmful substances (EU, 2000; Finnish Government, 2006). Currently, WWTPs in Finland, including Viikinmäki, monitor harmful substances according to Decree 1022/2006, where environmental quality standards (EQS) are presented for several compounds.

The priority substance regulation has not led to direct discharge limits for municipal WWTPs in Finland. Consequently, none of the 12 micropollutants listed in the new EU Directive 2024/3019 are currently subject to discharge limits, as Finland has no requirements for micropollutant removal at WWTPs. However, the 80 % removal efficiency requirement presented in the EU Directive 2024/3019 differs fundamentally from the concentration-based EQS of the WFD. Additionally, the European Commission has published a proposal COM/2022/540 to revise the WFD (2000/60/EC) and the Environmental Quality Standards Directive (2008/105/EC), proposing changes to both priority substances and their EQS (EU, 2022, 2008). Nevertheless, the EU Directive 2024/3019 represents the most immediate and significant regulatory change for Finnish WWTPs, including Viikinmäki.

Regarding phosphorus removal, Viikinmäki WWTP's current environmental permit sets stricter requirements than those of the new EU Directive 2024/3019. Current permit limits at Viikinmäki WWTP are <0.3 mg/L TP with >95 % removal efficiency (HSY, 2025). Additionally, HSY has its own, even stricter discharge targets for phosphorus removal. In the year 2024, HSY's target for yearly phosphorus discharge was 26 t/year, which already requires optimal performance from existing treatment process of HSY's Viikinmäki and Blominmäki WWTPs (HSY, 2025). Current performance shows that Viikinmäki WWTP consistently achieves effluent TP concentrations of approximately 0.19 mg/L, with an average removal efficiency of 97 % (HSY, 2025). However, HSY's future targets for phosphorus removal may require average annual effluent concentrations of 0.1 mg/L TP, necessitating the development of advanced phosphorus removal processes at Viikinmäki WWTP (Rossi, 2019).

2.2 Granular activated carbon (GAC)

GAC filtration is one of the most established technologies for micropollutant removal in advanced wastewater treatment. This section presents the physical and chemical properties of GAC (Section 2.2.1), factors affecting its performance (Section 2.2.2), and its application for micropollutant removal (Section 2.2.3). Performance monitoring strategies are discussed in Section 2.2.4, followed by the use of UV_{254} as a surrogate parameter for micropollutant removal (Section 2.2.5). Finally, filter configurations and operational aspects (Section 2.2.6) and design criteria (Section 2.2.7) are presented.

2.2.1 Physical and chemical properties

GAC is a highly porous material characterized by an extensive internal surface area, which enables efficient adsorption of organic micropollutants. Commercial GAC is primarily manufactured from coal, wood, coconut shells, and other materials containing carbon, which are then activated by thermal, physical or chemical processes (Bansal and Goyal, 2005). On the molecular level, the GAC structure consists of graphene layers which are composed of microcrystalline regions forming the pore structure between them (Çeçen and Aktaş, 2011; Marsh and Reinoso, 2006). The arrangement is similar to perfectly crystalline graphite but differs from it by non-uniform stacking order and structure creating highly reactive edge sites (Marsh and Reinoso, 2006). The GAC surface is hydrophobic and oleophilic, meaning that it repels water and attracts oils, organic compounds and other nonpolar impurities by adsorbing them onto its surface (Bansal and Goyal, 2005; Çeçen and Aktaş, 2011).

Adsorption in GAC occurs when dissolved organic molecules in water adhere to the carbon surface, primarily through physical means such as van der Waals forces (Worch, 2012). The adsorption capacity depends on the pore size distribution, which can be divided into three categories: macropores (>50 nm), mesopores (2–50 nm), and micropores (<2 nm). The pore structure of GAC is presented in Figure 1. Macropores and mesopores mainly function as transport channels that allow molecules to access the interior of carbon granules (Worch, 2012). Macropores can adsorb large particles, but if the particles are too large relative to the pore size, the macroporous region may become clogged (Piai et al., 2019). Micropores account for the majority of adsorption sites due to their substantially high surface area compared to volume, making them essential for the adsorption of small organic compounds (Çeçen and Aktaş, 2011). The pore size of GAC is therefore proportional to the size of the molecules to be adsorbed.

The particle size of GAC is defined using two different mesh sizes. The most common GAC mesh size is 12x40 (0.42–1.70 mm) and 8x30 (0.6–2.36 mm), since they provide an appropriate balance between the size, contact area and head loss performance for fixed-bed filter configuration (Elavarthi, 2021). Çeçen and Aktaş (2011) have suggested that GAC in approximately 12x40 mesh size is the most cost-effective for liquid-phase adsorption. When selecting appropriate particle size, the targeted adsorption capacity and hydraulic properties of the filter must be considered. Smaller particle size improves adsorption capacity due to larger specific surface area (Corwin and Summers, 2010). Additionally, smaller particles have been reported to prolong the operation time till the breakthrough compared to coarse GAC, likely due to reduced internal diffusion distance in finer GAC (Köpping et al., 2020). However, finer GAC can increase head losses and lead to shorter backwash intervals or promote filter clogging compared to coarse GAC (Altmann et al., 2016b).

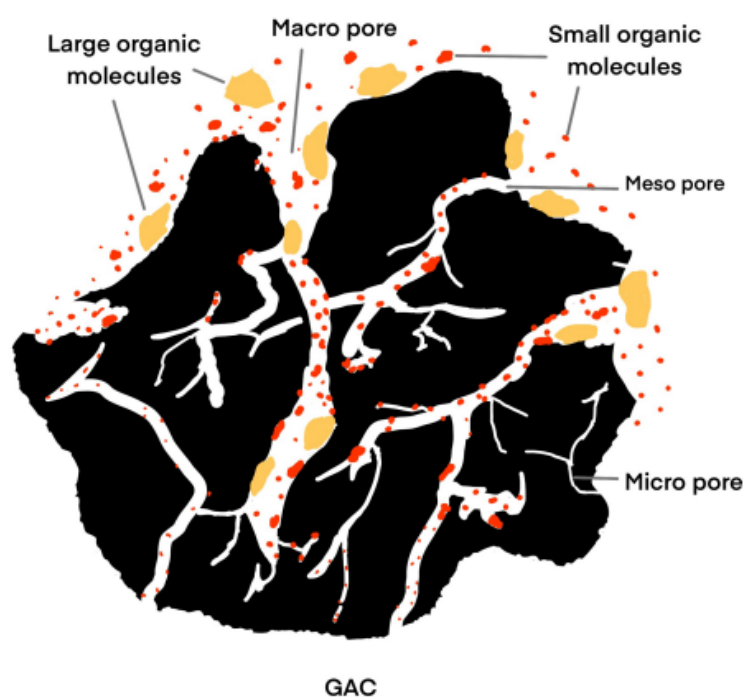


Figure 1. GAC pore structure (Elavarthi, 2021).

2.2.2 Factors affecting GAC performance

Many factors affect GAC performance, including water quality parameters, adsorbent and adsorbate properties (Çeçen and Aktaş, 2011; Marsh and Reinoso, 2006). In this context, the adsorbent refers to GAC and the adsorbate refers to organic micropollutants adsorbed with GAC. As discussed

in previous Section 2.2.1, adsorbent properties include GAC surface area, porosity, and chemical properties of the GAC surface can influence GAC performance. Similarly, the performance can be affected by the physical and chemical properties of the adsorbate including molecular weight, polarity and solubility. Nonpolar or weakly polar molecules are well adsorbed, while highly water-soluble, low molecular weight substances, such as ethanol, cannot be effectively removed with GAC (Worch, 2012).

Water quality parameters, such as pH, temperature and dissolved organic carbon (DOC) also have a role in the adsorption process. The pH of the water significantly affects micropollutant adsorption due to changes in the ionization state of both the compounds and the carbon surface (Bansal and Goyal, 2005; Worch, 2012). Neutral pH conditions typically provide optimal adsorption for pharmaceutical compounds and other micropollutants (Benstoem et al., 2017). Water temperature affects the affinity and diffusion of the compounds, and adsorption typically increases as temperature decreases, if the adsorption is an exothermic reaction (Çeçen and Aktaş, 2011; Worch, 2012). The primary limitation for GAC performance is the high DOC concentration in wastewater, typically between 7–10 mg DOC/L (Benstoem et al., 2017). DOC creates competitive adsorption conditions that significantly impact micropollutant removal and carbon service life (Benstoem et al., 2017).

2.2.3 Removal of organic micropollutants in wastewater

GAC is widely applied in advanced wastewater treatment for the removal of organic micropollutants due to its large surface area and versatile adsorption capacity of dissolved substances from water. However, the removal efficiency depends strongly on the molecular properties of the adsorbates, such as size, hydrophobicity and charge (Marsh and Reinoso, 2006).

Hydrophobic and aromatic compounds with low solubility, such as carbamazepine and benzotriazole, can achieve >80 % removal through noncovalent forces and hydrophobic interactions (Altmann et al., 2016b). Moderately adsorbing compounds, such as diclofenac, show variable performance influenced by water quality, pH and GAC type (Benstoem et al., 2017). Poorly adsorbing compounds are highly soluble and typically display limited removal due to low affinity and competition with natural organic matter (Çeçen and Aktaş, 2011). Besides the molecular properties of the individual compounds, the presence of multiple micropollutants create competition for available sites on the GAC surface, which can reduce the removal efficiency for individual compounds (Benstoem et al., 2017).

In Switzerland, advanced wastewater treatment systems for micropollutant removal and full-scale GAC systems have been implemented for over a decade. Full-scale performance from Swiss WWTPs shows removal rates of 80 % for many indicator compounds, with some plants achieving up to 90 % removal with GAC filtration combined with ozonation (Wunderlin and Bitterwolf, 2025). The 80 % limit is set by the Swiss legislation, and the GAC is to be regenerated when the removal efficiency decreases below this limit. The Swiss experience provides important operational aspects for GAC filtration systems and emphasizes the importance of pilot testing due to differences in GAC performance across WWTPs (Böhler et al., 2022). Monitoring strategies including DOC, UV absorbance at 254 nm (UV₂₅₄) and indicator micropollutant compounds have also been recommended (Benstoem et al., 2017; Böhler et al., 2022). Performance monitoring, process configurations and filter design criteria are presented in following Sections 2.2.4, 2.2.6, 2.2.7.

2.2.4 Performance monitoring

Monitoring GAC performance requires multiple parameters that reflect both current treatment performance and remaining service life. Key parameters include influent and effluent quality, breakthrough of selected indicator compounds, and hydraulic performance through head loss monitoring (Kennedy et al., 2015).

Indicator compounds are essential for detecting exhaustion and optimizing GAC replacement. For example, carbamazepine is widely used as an indicator due to its good adsorbability and frequent occurrence in wastewater, allowing reliable breakthrough monitoring under different operating conditions (Benstoem et al., 2017). To further predict the breakthrough performance of different compounds, the concept of breakthrough curves and mass transfer zone (MTZ) is often applied.

Breakthrough curves describe the progressive increase in adsorbate effluent concentration as adsorption sites become saturated, typically moving from an initial removal phase to a breakthrough phase with increasing concentrations, and finally to exhaustion with minimal removal at equilibrium (Merle et al., 2020). Figure 2 presents typical breakthrough characteristics in a fixed-bed GAC adsorber. The shape of the breakthrough curve depends on the compound properties, operational conditions, and influent characteristics (Çeçen and Aktaş, 2011; Worch, 2012). MTZ is an important concept for understanding breakthrough behaviour in fixed-bed systems, as it represents the region in the GAC bed where adsorption is actively occurring (Worch, 2012). Therefore, the movement of MTZ through the bed determines the timing of the breakthrough (Çeçen and Aktaş, 2011).

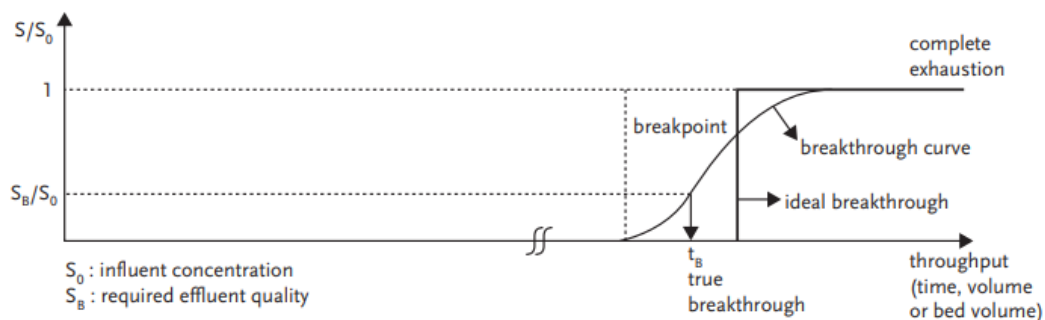


Figure 2. Breakthrough characteristics in a fixed-bed GAC adsorber (Çeçen and Aktaş, 2011).

Continuous monitoring of surrogate parameters, such as UV absorbance, can provide real-time performance assessment (Altmann et al., 2016a). UV absorbance as a surrogate parameter for micropollutant removal is discussed in the following Section 2.2.5. Rapid small-scale column tests (RSSCT) have also been used as a tool for breakthrough prediction but often overestimate full-scale performance due to reduced clogging effects with smaller particle sizes used in laboratory testing (Merle et al., 2020).

2.2.5 UV₂₅₄ as a surrogate parameter for micropollutant removal

UV₂₅₄ has been identified as a practical surrogate parameter for monitoring micropollutant removal in activated carbon processes (Altmann et al., 2016a; Anumol et al., 2015). While other wavelengths have also been investigated, UV₂₅₄ has established itself as the most commonly used parameter due to its higher sensitivity and proven correlation with micropollutant removal applications (Anumol et al., 2015; Wittmer et al., 2015).

Studies have demonstrated strong linear correlations between UV₂₅₄ reduction and micropollutant removal, and the correlations appear to be independent of water matrix composition (Anumol et al., 2015). Anumol et al. (2015) have reported correlation coefficients of $R^2 > 0.7$ for eight out of 13 tested compounds for GAC adsorption in RSSCT. Similarly, Altmann et al. (2016a) reported excellent linear correlations ($R^2 > 0.8$) for nine out of 12 compounds in lab-scale powdered activated carbon (PAC) adsorption batch tests. Altmann et al. (2016a) have also proven that UV₂₅₄ can serve as a reliable indicator for monitoring and controlling micropollutant removal efficiency in pilot-scale experiments. However, further research in WWTPs is needed to assess how storm events and seasonal variations influence UV₂₅₄ and to define site-specific control parameters, indicator substances, and target removal efficiencies for each WWTP (Wittmer et al., 2015).

According to Anumol et al. (2015), only samples with micropollutant removals between 5 % and 95 % should be chosen for correlation models. High or low removal rates might lead to clustering of data points and bias the R^2 and other correlation values (Anumol et al., 2015). Additionally, according to Sauter et al. (2021), the micropollutant reductions should only be calculated if the influent concentration is at least 5 times the limit of quantification (LOQ). If the influent concentration condition is fulfilled but the relative effluent concentration is below the LOQ, the removal can be calculated using $1/2$ LOQ as effluent concentration (Sauter et al., 2021).

2.2.6 Filter configurations and operation

GAC filters can be operated in two hydraulic configurations: upflow and downflow filters. The main reactor types are fixed, expanded and fluidized beds (Çeçen and Aktaş, 2011). In upflow filters, water is fed upward from the bottom of the filter bed, providing better utilization of the entire filter bed and lower head loss (Altmann et al., 2016b). However, Altmann et al. (2016b) have also stated that upflow systems may be more susceptible to particle breakthrough.

In downflow systems, water flows by gravity from the top of the filter through the carbon bed, offering simple operation and maintenance. A downflow filter with low flow velocities usually functions as a fixed-bed reactor, which is commonly used in wastewater treatment (Çeçen and Aktaş, 2011). Downflow filters must be regularly backwashed, as downflow filtration may result in particle accumulation in the upper layer and therefore rapid head loss development (Altmann et al., 2016b; Çeçen and Aktaş, 2011)

Backwashing is essential for sustaining GAC filter performance by removing accumulated particulates, preventing excessive head loss, and maintaining uniform flow distribution (Corwin and Summers, 2011). Backwash can be triggered based on time, head loss or turbidity. The frequency and intensity of backwashing depend on influent load, system design, and allowable head loss. Research by Kirchen et al. (2024) demonstrated that different backwashing modes had no impact on the removal of dissolved substances but can significantly affect particulate matter in the filter effluent. Altmann et al. (2016b) described a backwash procedure for a downflow GAC pilot treating wastewater, consisting of 45–90 seconds of air scour followed by 15 minutes of water backwash. Although backwash durations are rarely reported for wastewater applications, the regime applied by Altmann et al. (2016b) was comparable to those typically used in drinking water treatment (Emelko et al., 2006; Pang et al., 2005). Therefore, the Altmann et al. (2016b) procedure can be used as a baseline for designing downflow GAC pilot backwash operation. Usually, the backwashed water is recycled within the

treatment plant, for example, to the beginning of the WWTP process (STOWA, 2023).

2.2.7 Filter design criteria

Empty bed contact time (EBCT) is one of the most critical design parameter for GAC systems and directly relates to the adsorption efficiency of the system (Çeçen and Aktaş, 2011; Worch, 2012). EBCT characterizes the theoretical time that water spends in contact with the GAC bed. The basic calculation for EBCT is equal to the bed volume divided by the flow rate, following Equation 1.

$$EBCT = \frac{V}{Q} \quad (1)$$

where

V = volume of the GAC bed

Q = flow rate

Current design guidelines recommend EBCT values ranging from 20 to 30 minutes for effective micropollutant removal, although optimal values can vary significantly depending on target compounds and influent water characteristics (Böhler et al., 2022; Wunderlin and Bitterwolf, 2025).

Main parameters influencing the EBCT are GAC bed depth and hydraulic loading rate (HLR) (Çeçen and Aktaş, 2011). The GAC bed depth typically ranges from 1.5 to 2.5 m, with finer GAC requiring smaller bed depths, especially for influents with high TSS concentrations (Böhler et al., 2023). Consequently, larger bed depths are applied for low TSS concentrations.

With respect to the bed depth, HLR expresses the velocity of liquid moving in a GAC bed along the cross-sectional area and bed depth. The HLR is calculated by dividing flow rate by the surface area of the GAC bed, as seen in Equation 2. In tertiary wastewater treatment, HLR typically ranges between 7 and 16 m/h (Çeçen and Aktaş, 2011).

$$HLR = \frac{Q}{A} \quad (2)$$

where

Q = flow rate

A = surface area of GAC bed

Another important parameter is the bed volume (BV). BV represents the cumulative volume of water treated relative to the filter bed volume, as shown in Equation 3 below.

$$BV = \frac{V_L}{V} \quad (3)$$

where

V_L = volume of water treated

V = volume of the GAC bed

The BV serves as a critical parameter for determining the replacement schedule of GAC media (Worch, 2012). Replacement of GAC is generally required after 20 000–30 000 BVs, although the range depends on indicator micropollutants, influent quality, target removal efficiency and operating conditions (Wunderlin and Bitterwolf, 2025). The typical service life of 20 000–30 000 BVs corresponds to approximately 1–3 years of operation (Wunderlin and Bitterwolf, 2025). Summary of typical design parameters is shown in Table 2.

Table 2. Summary of typical GAC filter design parameters for wastewater treatment.

Parameter	Typical range	Reference
Empty bed contact time (EBCT)	20–30 min	(Böhler et al., 2022; Çeçen and Aktaş, 2011; Worch, 2012; Wunderlin and Bitterwolf, 2025)
Hydraulic loading rate (HLR)	7–16 m/h	(Çeçen and Aktaş, 2011)
Bed volume (BV)	20 000–30 000 BVs (1–3 years of operation)	(Wunderlin and Bitterwolf, 2025)
Bed depth	1.5–2.5 m	(Böhler et al., 2023; Çeçen and Aktaş, 2011)

2.3 Phosphorus removal fundamentals

Phosphorus removal in wastewater treatment requires understanding of both the chemical forms of phosphorus and mechanisms for their removal. This section first describes phosphorus fractions in wastewater (Section 2.3.1), followed by the chemical processes involved in phosphorus removal (Section 2.3.2). The terminology used in this study is clarified in Section 2.3.3, and the principles of phosphorus removal combined with GAC filtration are presented in Section 2.3.4.

2.3.1 Phosphorus fractions

Phosphorus occurs in wastewater in several chemical forms that differ in reactivity, bioavailability, and removability (Benjamin, 2013; Gu, 2014; Li and Brett, 2015). Total phosphorus (TP) is the primary regulatory parameter for wastewater discharge limits and represents the sum of all phosphorus forms in the effluent (Benjamin, 2013). However, understanding the distribution among different chemical forms within TP is essential for optimising treatment processes and achieving low effluent concentrations (Gonzalez Medeiros et al., 2005; Gu, 2014; Neethling et al., 2007).

Phosphorus fractions are defined by analytical separation steps. The main phosphorus fractions are presented in Table 3. Total phosphorus divides into two primary fractions: soluble and particulate phosphorus. To separate soluble and particulate forms of TP, the sample is filtered through a 0.45 μm membrane (Maher and Woo, 1998). Soluble and particulate forms are further divided into reactive and non-reactive fractions. To distinguish reactive phosphorus from non-reactive species, colorimetric analysis is applied (Maher and Woo, 1998). Separating phosphorus into soluble and particulate fractions with subsequent reactive and non-reactive analysis provides an effective method for interpreting phosphorus removal performance (Neethling et al., 2007).

Soluble phosphorus separates into soluble reactive phosphorus and soluble non-reactive phosphorus. Soluble reactive phosphorus consists predominantly of orthophosphate ($\text{PO}_4\text{-P}$), which exists in pH-dependent ionic forms: PO_4^{3-} , HPO_4^{2-} , H_2PO_4^- , and H_3PO_4 (Gu, 2014; Maher and Woo, 1998). $\text{PO}_4\text{-P}$ is the bioavailable inorganic form of phosphorus and represents the primary target for chemical precipitation processes, where metal salts react with dissolved $\text{PO}_4\text{-P}$ to form insoluble precipitates and metal hydroxides (Benjamin, 2013; Dueñas et al., 2003; Gu, 2014). In advanced phosphorus removal processes, nearly all soluble reactive phosphorus can be eliminated (Carrillo et al., 2020; Gu, 2014).

The soluble non-reactive fraction comprises soluble acid-hydrolysable phosphorus and soluble organic phosphorus (Gu, 2014). The acid-hydrolysable fraction includes primarily polyphosphates, and the soluble organic fraction includes phosphate esters, phosphoproteins, and phosphonates (Benjamin, 2013; Gu, 2014). The soluble organic fraction does not react with traditional metal salt coagulants and exhibits significantly lower removal efficiency than phosphates or inorganic phosphorus (Gu, 2014; Li and Brett, 2015; Neethling et al., 2007). Therefore, the refractory soluble organic phosphorus is commonly the dominant fraction in residual effluent phosphorus at ultra-low TP concentrations (Gu, 2014; Li and Brett, 2015; Neethling et al., 2007).

Similarly to the soluble phosphorus fractions, particulate phosphorus divides into particulate reactive phosphorus and particulate non-reactive phosphorus. The non-reactive particulate fraction comprises particulate acid-hydrolysable phosphorus and particulate organic phosphorus (Gu, 2014). Effective removal of particulate phosphorus fractions requires efficient solid-liquid separation through sedimentation, flotation, or filtration processes (Benjamin, 2013; Gu, 2014). Different treatment technologies achieve varying removal efficiencies for different phosphorus fractions, with proper chemical dose control being critical especially for minimising soluble reactive phosphorus in the effluent (Neethling et al., 2007).

Table 3. Phosphorus fractions (adapted from Carrillo et al., 2020; Gu, 2014; Maher and Woo, 1998; WRF 2019).

Total P (TP)					
Total soluble P (TSP)			Total particulate P (TpP)		
Soluble reactive P (SRP)	Soluble non-reactive P (SNRP)		Particulate reactive P (pRP)	Particulate non-reactive P (pNRP)	
	Soluble acid-hydrolysable P (SAHP)	Soluble organic P (SOP)		Particulate acid-hydrolysable P (pAHP)	Particulate organic P (pOP)

2.3.2 Chemical phosphorus removal

Chemical phosphorus removal involves precipitation, coagulation, and flocculation processes, which usually occur simultaneously when particle-destabilizing chemicals, typically metal coagulants, are added to wastewater and thoroughly mixed (Bratby, 2016; Shammass et al., 2021). The addition of chemicals leads to a change in the solubility equilibrium of phosphorus fractions, resulting in the formation of insoluble compounds and the

aggregation of particles into flocs through combined chemical and physical mechanisms (Bratby, 2016; Shammas et al., 2021).

Precipitation is a chemical process in which soluble phosphorus reacts with added metal ions to form metal–phosphate and metal-hydroxide compounds (Benjamin, 2013; Bratby, 2016; Shammas et al., 2021). Coagulation, however, is primarily a charge-neutralization and particle-destabilization process, where small microflocs are formed (Bratby, 2016; Shammas et al., 2021). Flocculation refers to the aggregation stage, where gentle mixing promotes adhesion between the destabilized particles, forming larger, settleable flocs (Benjamin, 2013; Bratby, 2016). Therefore, precipitation implies a phase transition from soluble to solid species, whereas coagulation and flocculation describe the formation of larger aggregates from existing solid particles (Shammas et al., 2021). In practical applications, rapid mixing is required at coagulant dosing, followed by gentle mixing to promote floc growth without breaking the particles (Benjamin, 2013).

The most commonly used metal coagulants are aluminium and iron salts (Benjamin, 2013; Stuetz and Stephenson, 2009). When aluminium-based coagulants are dosed, they form positively charged hydroxo complexes (e.g. $\text{Al}(\text{OH})_2^+$, $\text{Al}(\text{OH})_3^+$) that destabilize negatively charged colloids and phosphate ions (Bratby, 2016; Shammas et al., 2021). This charge neutralization initiates coagulation, while flocculation aggregates the destabilized particles through kinetic mechanisms (Bratby, 2016). Simultaneously, chemical precipitation produces aluminium hydroxide and aluminium phosphate solids that contribute to floc growth (Benjamin, 2013; Bratby, 2016). The optimal pH for phosphorus removal using aluminium coagulants is usually within the range of 5.5 to 6.0 (Bratby, 2016). In acidic conditions, metal phosphates are formed, whereas at higher pH, metal hydroxide formation is favoured (Bratby, 2016; Shammas et al., 2021). In chemical phosphorus removal, $\text{PO}_4\text{-P}$ is the primary target for chemical precipitation processes (Benjamin, 2013; Gu, 2014). Additionally, phosphate ions can adsorb onto the surfaces of metal hydroxide precipitates, contributing to overall phosphorus removal beyond direct precipitation (Bratby, 2016). Limited adsorption can also occur onto the GAC surface, which is further discussed in Section 2.3.4. Overview of chemical phosphorus removal processes is presented in Figure 3.

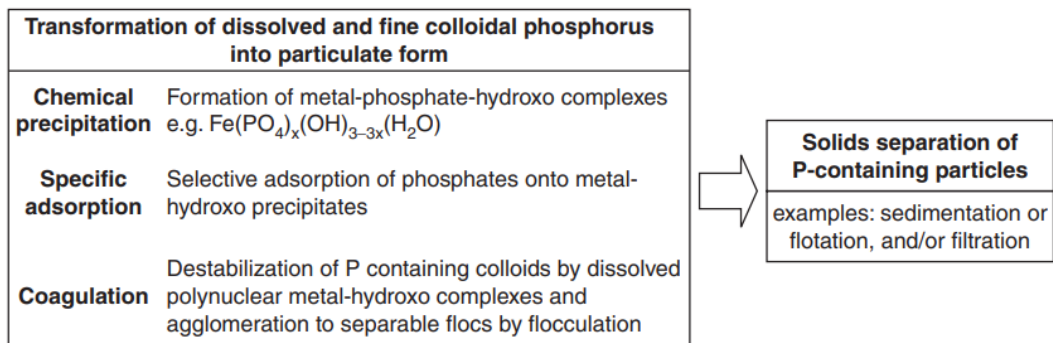


Figure 3. Overview of chemical phosphorus removal processes (Bratby, 2016).

2.3.3 Terminology used in the present study

In the scope of this study, the actual distinction between precipitation, coagulation, flocculation and adsorption mechanisms involved in phosphorus removal is not presented. The focus is not on the specific chemical reactions involved, but rather on evaluating whether effective phosphorus removal can be achieved by combining chemical phosphorus removal with GAC filtration.

Therefore, in this study, the particle-destabilizing process is described as coagulation rather than precipitation, emphasizing that the formation of stable flocs is critical for efficient separation in the subsequent GAC filtration. The distinction is important, as precipitation produces fine, often non-settleable particles, whereas coagulation and flocculation describe the destabilization and aggregation of particles into settleable and filterable flocs suitable for phosphorus removal (Shammas et al., 2021; Stuetz and Stephenson, 2009). However, in real wastewater systems, the boundary between precipitation, coagulation and flocculation is difficult to distinguish, as the processes occur simultaneously (Shammas et al., 2021). Furthermore, the literature shows inconsistent terminology, with the terms precipitant, coagulant and flocculant used both interchangeably and as distinct terms depending on the author (Benjamin, 2013). In this study, particle-destabilizing chemicals are referred to as coagulants. The gentle mixing of the coagulant is referred to as flocculation in this study, to further emphasize the particle aggregation and floc growth step.

2.3.4 Phosphorus removal combined with GAC filtration

Unlike the direct adsorption onto GAC for micropollutants, GAC exhibits very limited phosphate adsorption capacity (Acosta et al., 2021;

Shafiquzzaman et al., 2025). This limited adsorption capacity occurs since the hydrophobic and oleophilic GAC surface preferentially adsorbs nonpolar organic compounds rather than hydrophilic ionic species such as phosphate (Çeçen and Aktaş, 2011). Acosta et al. (2021) have emphasized that phosphorus compounds do not usually adsorb onto standard GAC surface, therefore, the addition of a coagulant is necessary for effective phosphorus removal. However, Ouakouak and Youcef (2016) have demonstrated in batch adsorption tests using synthetic phosphate solutions that GAC can achieve up to 40 % removal of phosphates in ideal laboratory conditions with distilled water. Ouakouak and Youcef (2016) proposed that the process is reversible and strongly pH-dependent, and that the adsorption kinetics can be described with a pseudo-second-order kinetics model. However, real wastewater systems are not comparable to ideal laboratory conditions with synthetic solutions, making the practical phosphorus adsorption applications limited.

Modified forms of activated carbon can achieve enhanced phosphate adsorption (Mahardika et al., 2018; Seo et al., 2025). Mahardika et al. (2018) developed ferrihydrite-impregnated GAC, demonstrating that preoxidation of GAC surface using strong acids creates active functional groups that enhance iron binding. This modification achieved a maximum phosphate adsorption capacity of 5.73 mg P/g GAC, which is more than double than for pristine GAC. Similarly, Seo et al. (2025) developed iron-modified activated carbon using ferric chloride impregnation, achieving approximately twice the phosphate removal efficiency compared to unmodified activated carbon.

Therefore, it can be stated that efficient phosphorus adsorption requires either chemical modification, e.g. by metal impregnation of the GAC media, or chemical coagulation integrated with GAC filtration. The mechanisms for phosphorus and micropollutant removal are fundamentally different, which is critical for understanding the combined coagulation and GAC system investigated in this study. Organic micropollutants adsorb directly onto the hydrophobic GAC surface, while phosphorus removal in unmodified GAC systems depends on chemical coagulation followed by physical filtration and limited adsorption onto GAC surface (Acosta et al., 2021; Altmann et al., 2016b; Telgmann et al., 2020). This means that the GAC filter serves as both an adsorbent for organic compounds and as a mechanical filter for phosphorus-containing flocs. Therefore, the phosphorus removal is mostly dependent on the efficiency of the upstream chemical phosphorus removal process rather than the adsorptive properties of the GAC media itself. Previous studies on combined coagulation and GAC filtration processes are presented in the following Section 2.4.

2.4 Previous studies on combined processes

Integrating GAC filtration with chemical coagulation offers a promising treatment approach for simultaneous phosphorus and micropollutant removal. The feasibility of combined coagulation and GAC filtration process has been identified in various recent studies (Altmann et al., 2016b; Kramer et al., 2017; Locher and Blind, 2024; Sauter et al., 2021; STOWA, 2023; Telgmann et al., 2020). In this section, the process configurations (Section 2.4.1), as well as results of relevant European studies are presented (Section 2.4.2), highlighting the different coagulant dosing strategies and phosphorus removal efficiencies. Operational considerations and knowledge gaps are discussed in Section 2.4.3.

2.4.1 Process configurations

In combined treatment systems, efficient phosphorus removal requires the addition of coagulants, typically iron- or aluminium-based salts, upstream of the GAC filter (Acosta et al., 2021). Metal coagulants are dosed to form phosphorus-containing flocs that are further removed by GAC filter bed through mechanical filtration and backwashing of the filter (Altmann et al., 2016b; Shafiquzzaman et al., 2025; Telgmann et al., 2020). Alternative pretreatment configurations prior to GAC filtration may include disc filtration or cloth filtration to reduce suspended solids and prevent clogging of the GAC bed (Kirchen et al., 2024). GAC filtration can be implemented in various configurations, including downflow gravity filters, upflow filters, or dual-media filtration systems (Altmann et al., 2016b). In fixed bed systems, the solid material from coagulation and flocculation is retained and removed within the GAC filter by backwashing (Telgmann et al., 2020). However, the backwashing frequency represents one of the key operational limits in combined phosphorus and micropollutant removal processes using GAC as the filtration step (Telgmann et al., 2020). Operational considerations are further discussed in Section 2.4.3.

2.4.2 Pilot-scale experiments in Germany and in the Netherlands

The addition of chemical coagulants prior to GAC filtration has shown feasible results across different German and Dutch pilot studies. Altmann et al. (2016b) used ferric chloride (FeCl_3) dosing at 4–5 mg Fe/L, with a molar ratio of 4–5 mol Fe/reactive phosphorus for inline coagulation. In their pilot-scale study at Berlin-Munchehofe WWTP, the coagulant was dosed into a static mixer, followed by a flocculation tank with a hydraulic retention time (HRT) of 6 minutes. This dosing strategy achieved TP concentrations below 0.1 mg/L in dual media GAC filter (influent 0.54 mg/L), consisting of a 1.4 m GAC bed above a 0.6 m sand bed. The influent TP concentration was around

0.5 mg/L. The EBCT for the process was 14 minutes. Similar phosphorus removal performance was achieved with mono-media upflow GAC filter, with an EBCT of 19 minutes (Altmann et al., 2016b). Well-adsorbing micropollutants (e.g. benzotriazole and carbamazepine) were removed by >80 % up to 8 000–10 000 BVs, whereas weakly adsorbing micropollutants (e.g. sulfamethoxazole) showed removals of <80 % at less than 5 000 BVs. Both filtration processes effectively removed suspended solids, achieving effluent concentrations of 1 mg/L TSS.

Telgmann et al. (2020) tested pilot-scale GAC filters with three different GAC types after initial operating of the filters with dual-bed anthracite-sand media. They used ferric chloride dosing at a maximum of 2 mg Fe/L, limiting the production of flocs. The study showed that influent TP concentrations of around 0.3 mg/L required minimal dosing of coagulant, while concentrations near 0.6 mg/L TP demanded higher doses to avoid filter breakthrough. For influent TP concentrations of 0.25 to 0.3 mg/L, effluent concentrations of around 0.1 mg/L TP were achieved with finer types of GACs. Telgmann et al. (2020) tested three different GAC sizes, showing that coarse GAC (4x8 mesh) achieved poor micropollutant removal due to insufficient contact time, while finer GAC (8x14 mesh) achieved high removal for most compounds. However, due to the finer mesh size, the filter required backwashing up to four times per 24 hours, which is far too often for efficient operation. After 11 000 BVs, well- and medium-adsorbing micropollutants were removed to at least 60 % in 8x14 mesh GAC filter (EBCT = 14 min). For the 4x8 mesh filter bed, only 40 % adsorption for very well adsorbing compounds were achieved, probably due to low EBCT (7 min). Both grain size GAC filters led to low TSS levels, below 2 mg/L TSS.

Locher and Blind (2024) operated a pilot-scale process with continuously backwashed GAC filters at Emmingen-Liptingen WWTP. FeCl₃ was used as a coagulant, with a dosage of 4.5 mol Fe/mol PO₄-P. The process consisted of three GAC filters, of which two were continuously fed with coagulant and one filter was operated as a reference line without coagulation. The coagulant was dosed upstream the GAC filters with a dynamic mixer. GAC with a mesh size of 8x30 was used in each filter. During the 18-month trial, they achieved approximately 50 % TP removal with effluent concentrations of 0.2 mg/L (influent 0.5–0.8 mg/L). The process was also suitable for PO₄-P removal and achieved approximately 70 % removal efficiency without significantly affecting micropollutant removal or reactivation of the GAC media (Locher and Blind, 2024). An average of 73–76 % removal for seven monitored micropollutants (e.g. metoprolol, benzotriazole and amisulpride) were analysed over the 18-month test period of 32 000 BVs.

Dual-media configurations have also shown promising results for combined micropollutant and phosphorus removal. Sauter et al. (2021) studied ozonation followed by three parallel filter columns, consisting of biologically activated carbon (BAC) filter, dual-media sand-BAC filter and dual-media sand-anthracite filter at Schoenerlinde WWTP. The dual-media filters were operated with EBCTs of 10–20 minutes and dosed with FeCl_3 with a dosage of 1.8 mg Fe/L (4.4 mol Fe/mol $\text{PO}_4\text{-P}$). Results showed that achieving TP concentrations of 0.1 mg/L is feasible (influent 0.6 mg/L), however, the achievable effluent concentrations are limited by the share of the soluble non-reactive fraction in TP. Well-adsorbing compounds (metoprolol, oxypurinol and benzotriazole) achieved removals of 69 %, 76 %, and 91 %, respectively. The removals were presented for over 30 000 BVs.

In Dutch studies, combined treatment for simultaneous micropollutant and nutrient removal has been implemented successfully through the 1- and O₃-STEP technologies at Horstermeer WWTP (Kramer et al., 2017; STOWA, 2023). The 1-STEP process combines denitrification, coagulation-flocculation and GAC filtration for enhanced phosphate, nitrate and micropollutant removal (Kramer et al., 2017). With the 1-STEP filter, TP concentrations below 0.15 mg/L were achieved. The backwash interval was 12 hours.

The O₃-process was developed from the 1-STEP filter by integrating biological nutrient removal (methanol dosed for denitrification), ozonation (0.4 g O₃/g DOC), chemical coagulation with PAX (4–5 mol Al: $\text{PO}_4\text{-P}$), flocculation in the upper water level of the GAC filter (8 min) and downflow GAC filtration (EBCT 17 min) in a single treatment process. The O₃-process achieved TP concentrations of 0.1 mg/L (influent 0.21 mg/L) and $\text{PO}_4\text{-P}$ levels below 0.05 mg/L (STOWA, 2023). The process demonstrated comprehensive phosphorus fraction removal, effectively removing almost all $\text{PO}_4\text{-P}$, significant amounts of particulate phosphorus, and portions of metal-bound phosphorus, indicating broad applicability across different wastewater characteristics. The pilot study also demonstrated minimum of 80 % removal for 7 well-adsorbing indicator substances, with many micropollutants being removed by >90 %. The combination of ozone and GAC enables higher and broader micropollutant removal efficiency than the individual technologies alone. Summary of combined processes in relevant studies is presented in Table 4.

Table 4. Summary of combined processes in relevant pilot-scale studies.

Study	Process configuration	EBCT	Coagulant and dose	Flocculation HRT	Effluent TP (influent TP)
Altmann et al. (2016b)	FeCl ₃ + flocculation + dual-media sand-GAC filter	14–19 min	FeCl ₃ , 4–5 mg Fe/L	6 min	0.1 mg/L (influent 0.5 mg/L)
Telgmann et al. (2020)	FeCl ₃ + GAC filtration with three GAC types	7–14 min	FeCl ₃ , max 2 mg Fe/L	-	0.1 mg/L (influent 0.25–0.3 mg/L)
Locher and Blind (2024)	FeCl ₃ dosed via dynamic mixer + GAC filter	10–30 min	FeCl ₃ , 4–5 mol Al:PO ₄ -P	-	0.2 mg/L (influent 0.5–0.8 mg/L)
Sauter et al. (2021)	Ozonation + FeCl ₃ + dual-media sand-BAC filter	10–20 min	FeCl ₃ , 4.4 mol Al:P	-	0.1 mg/L (influent 0.6 mg/L)
STOWA (2023)	O ₃ -STEP: Ozonation + PAX coagulation + flocculation + GAC filter	17 min	PAX, 4 mol Al:PO ₄ -P	8 min	0.1 mg/L (influent 0.2 mg/L)

2.4.3 Operational considerations and knowledge gaps

The continuous dosing of coagulants increases the solids load on the GAC filter surface (Böhler et al., 2023; Zettl, 2023). According to Altmann et al. (2016b) coagulation with ferric chloride (4-5 mg Fe/L) can increase TSS concentrations in the GAC filter influent from approximately 2–3 mg/L to 12–15 mg/L that must be retained by the filter. The solids and flocs might also break down into smaller particles and be carried further into the filter bed, possibly leading to increased turbidity in the filter outlet, as well as clogging of the filter bed (Zettl, 2023). However, if the additional TSS concentration in the influent to the GAC filter is considered when designing the filtration system, the combined process can be seen as a promising advanced treatment method (Böhler et al., 2023).

Compared to upstream filters, the hydraulic conditions for floc formation are more favourable during downstream filtration, since the gentle mixing

conditions in the filter supernatant can support floc growth (Acosta et al., 2021). However, downflow filters require frequent backwashing, which leads to finer grains accumulating in top of the filter and coarse grains settling at the bottom, potentially causing excessive head loss and filter blocking (Acosta et al., 2021; Altmann et al., 2016b). Therefore, upflow filtration might provide better filter depth utilization and lower head loss compared to downflow filtration (Altmann et al., 2016b). However, upflow systems can also be more susceptible to particle breakthrough at longer backwash intervals (Altmann et al., 2016b).

Backwashing frequency represents one of the critical limiting factors in combined processes. GAC is particularly susceptible to abrasion compared to conventional filter media such as anthracite or sand, requiring careful optimization of backwashing intervals to minimize loss of adsorbent material (Corwin and Summers, 2011). Additionally, frequent backwashing consumes significant energy and water resources, which should be minimized for cost-effective operation (Crittenden et al., 2012). The optimal balance between filter run time and backwashing frequency depends on the particle load entering the filter bed, with typical target backwash cycles of approximately 24 hours in wastewater treatment applications (Boller and Kavanaugh, 1995; Crittenden et al., 2012).

The operating settings for the optimal dosage of the coagulant before the GAC filter still have to be studied, as well as the effectiveness of phosphorus removal in GAC filters (Acosta et al., 2021). While coagulation and flocculation are technically feasible to combine with GAC filtration, systematic studies examining the effects of coagulants on both treatment performance and GAC regeneration capability are still lacking (Böhler et al., 2023). Despite these knowledge gaps, pilot-scale studies have demonstrated that combined coagulation and GAC filtration can achieve effluent concentrations of 0.1 mg/L TP (Altmann et al., 2016b; Sauter et al., 2021; STOWA, 2023; Telgmann et al., 2020). Current understanding of the combined process suggests that coagulation and flocculation must be completed prior to GAC filtration (Böhler et al., 2023).

3 Research material and methods

This study investigated the combined removal of phosphorus and micropollutants by integrating chemical coagulation and GAC filtration. However, as GAC filtration typically achieves high micropollutant removal efficiency, the emphasis was placed on phosphorus removal performance, which remains a less investigated aspect of combined GAC treatment processes.

Experiments were conducted at HSY's Viikinmäki WWTP between April 2025 and October 2025, comprising three experimental scales: flocculation jar tests, laboratory-scale column experiments and pilot-scale column experiments. Both laboratory- and pilot-scale experiments were conducted at Viikinmäki WWTP. Analyses were performed at Viikinmäki laboratory and external laboratories, which are presented in Section 3.2. All experiments utilized regenerated GAC from HSY's Vanhakaupunki water treatment plant, with an average mesh size of 8x30. As no detailed GAC specifications were available for the regenerated GAC, Appendix A presents the commercial manufacturer's specifications for Filtrasorb 400, from which the GAC was originally regenerated from. Chemical coagulation was performed using Kemira's PAX-XL100, which was obtained from HSY's Blominmäki WWTP. Therefore, the focus is on aluminium-based coagulants, as PAX is used in both laboratory- and pilot-scale experiments.

The following sections describe the Viikinmäki WWTP process configuration (Section 3.1), analytical methods (Section 3.2), and detailed experimental procedures for each scale of investigation (Sections 3.3 and 3.4).

3.1 Viikinmäki wastewater treatment plant

The Viikinmäki WWTP was commissioned in 1994 and is the largest plant of its kind in Finland and in the Nordic countries. The plant treats wastewater from approximately 900 000 inhabitants in the city of Helsinki, eastern Vantaa, and six surrounding municipalities, serving both domestic and industrial sources. In the year 2024, the PE of Viikinmäki WWTP was 1 178 812 and the average influent flow was 292 564 m³/d (HSY, 2025). The plant is located mainly in underground rock caverns.

The treatment process of Viikinmäki WWTP is a conventional activated sludge process with post-denitrification (Figure 4). The process comprises mechanical, chemical and biological stages. Wastewater is pre-treated by screening and grit removal, followed by pre-aeration and primary sedimentation before the biological treatment stage. Ferrous sulphate

(FeSO_4) is used for phosphorus removal, and lime is added for alkalinity control. Phosphorus removal in Viikinmäki WWTP is discussed in more detail in the following Section 3.1.1. Total nitrogen is removed by biological treatment in denitrification-nitrification activated sludge process with nine parallel lines. Final polishing for nitrogen removal occurs in biological post-denitrification (post-DN) filters using methanol as a carbon source. Sludge is treated with anaerobic digestion, generating biogas that is used for heat and electricity production at the plant. The resulting sludge digestate is composted in Sipoo and used as a component in landscaping soils and as a fertilizer. The treated effluent is conveyed through a 16 km discharge tunnel to the Baltic Sea.

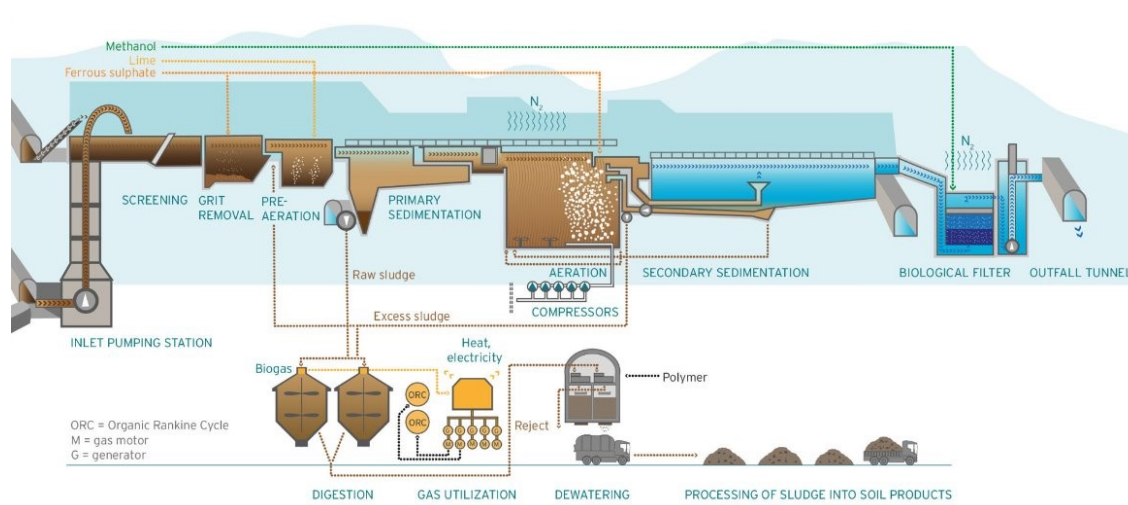


Figure 4. Viikinmäki WWTP treatment process.

3.1.1 Phosphorus removal

Phosphorus is removed at Viikinmäki WWTP by chemical precipitation using FeSO_4 in a two-stage precipitation configuration. The first dosing point of FeSO_4 is located at the grit removal chamber, and the second dosing point is before the secondary settlers. This dosing strategy decreases the overall coagulant consumption compared to single-point addition. The average FeSO_4 consumption is 68–84 mg/L, corresponding to approximately 7 500–8 700 tonnes annually (HSY, 2025). The formed precipitates are removed from the process bound to the sludge, which is treated in anaerobic digesters.

The limit of 0.1 mg/L TP in the effluent is used as a fundamental target for phosphorus removal in this study, based on HSY’s own discharge targets. Current performance shows that Viikinmäki WWTP consistently achieves effluent TP concentrations of approximately 0.19 mg/L, with an average removal efficiency of 97 % (HSY, 2025). However, achieving lower effluent TP concentrations is constrained by the post-DN filters, which require

adequate phosphorus for the growth and metabolism of the denitrifying bacteria. Therefore, the phosphorus concentration before the post-DN process must be maintained at a sufficient level to ensure proper biological nitrogen removal activity. Consequently, the target effluent limit of 0.1 mg/L TP presented in this study is not possible to achieve with the current process configuration.

3.1.2 Removal of micropollutants

Current micropollutant removal performance at Viikinmäki WWTP shows variable removal efficiency depending on the compounds. Table 5 presents average concentrations for the EU Directive 2024/3019 indicator substances in Viikinmäki influent and effluent, along with their corresponding removal efficiencies. If effluent concentrations were below the LOQ, removal percentages were calculated using half of the LOQ value, as recommended in literature (Sauter et al., 2021). If influent concentration was below the LOQ, removal efficiency could not be determined. Micropollutants were analysed as part of this study, alongside the pilot-scale micropollutant sampling. Total of six sampling events were conducted during this study. However, for Viikinmäki influent and effluent, results from five sampling events between 7 August and 25 September 2025 are shown in Table 5, as Viikinmäki influent concentration was not measured in the last sampling event (1 October). Measurement uncertainties and LOQ values are presented in Appendix B.

Amisulpride is only indicator substance that showed high removal efficiency (95 %) in the current treatment process at Viikinmäki WWTP during the measurement campaign. Most other indicator substances achieved moderate to low removal efficiencies, with some compounds showing even negative removal efficiencies, which may indicate transformation product formation or analytical variability. However, these results demonstrate that the conventional activated sludge process with post-DN filtration at Viikinmäki WWTP is insufficient to meet the 80 % removal requirement for micropollutants mandated by the EU Directive 2024/3019. Therefore, implementation of advanced treatment processes such as GAC filtration is necessary at Viikinmäki WWTP.

Table 5. Average concentrations for EU Directive 2024/3019 indicator substances in Viikinmäki influent and effluent and their removal efficiencies. Micropollutants were analysed as part of this study, alongside the pilot-scale measurement campaign.

Indicator substance	Viikinmäki influent, µg/L	Viikinmäki effluent, µg/L	Removal efficiency
Category 1 (substances that can be very easily treated)			
Amisulpride	0.11	<0.01	95 %
Carbamazepine	0.12	0.14	-18 %
Citalopram (+ Escitalopram)	0.20	0.15	22 %
Clarithromycin	<0.10	<0.01	-
Diclofenac	0.79	0.48	39 %
Hydrochlorothiazide	0.57	0.45	22 %
Metoprolol	0.17	0.19	-15 %
Venlafaxine	0.58	0.63	-8 %
Category 2 (substances that can be easily disposed of)			
Benzotriazole	2.4	1.6	35 %
Candesartan	0.92	0.85	8 %
Irbesartan	<0.10	<0.01	-
4- and 5-Methylbenzotriazole	0.73	0.58	20 %

3.2 Analytical methods

A set of analyses was performed to characterise the wastewater samples and to assess the removal efficiency of phosphorus and micropollutants. Analyses included TP, TSP and PO₄-P to evaluate removal mechanisms between particulate and soluble phosphorus fractions. Total and dissolved aluminium were measured to monitor coagulant behaviour and residual aluminium in the filter effluent. TSS analysis was included as solids affect both phosphorus removal through capturing particulate fractions and GAC filter performance. UV₂₅₄ was measured as a surrogate parameter for selected micropollutants regulated under the EU Directive 2024/3019. A list of analysed micropollutants is presented in Appendix B. Analyses were conducted at four laboratories: Viikinmäki WWTP laboratory, Metropolilab Oy, Eurofins Environment Testing Finland Oy and Aalto University Water Laboratory. Analytical methods, standards and laboratories are summarised in Table 6. Sampling points and frequencies are described in Sections 3.3.3 and 3.4.2.

At the Viikinmäki WWTP laboratory, aluminium and phosphate concentrations were analysed using Hach's LCK cuvette test kits (Figure 5) and a Hach DR 2800 spectrophotometer. Aluminium concentrations were measured using the LCK301 cuvette test, with a measurement range of 0.02–0.05 mg/L Al. The method is based on Chromazurol S, which forms a green-coloured complex with aluminium in weakly acidic solution. Similarly, PO₄-P and TP were analysed using the LCK349 cuvette test, with a measurement range of 0.05–1.5 mg/L PO₄-P. The phosphate test kit is based on phosphormolybdenum blue method, in which phosphate ions react with molybdate and antimony ions in an acidic solution to form a complex, which is then reduced by ascorbic acid to produce a blue-coloured compound. According to ISO 6878-1-1986 standard, TP was determined after heated acid digestion and PO₄-P was determined from 0.45 µm filtered samples without digestion. UV₂₅₄ was determined on a Uvitec™ Field Meter. UV analyses included blank samples, duplicates and calibration verification. The UV₂₅₄ absorbance method is an internal spectrophotometry method, which was adapted from the Standard Methods for the Examination of Water and Wastewater 5910, UV-adsorbing organic constituents (Standard Methods For the Examination of Water and Wastewater, 2017).

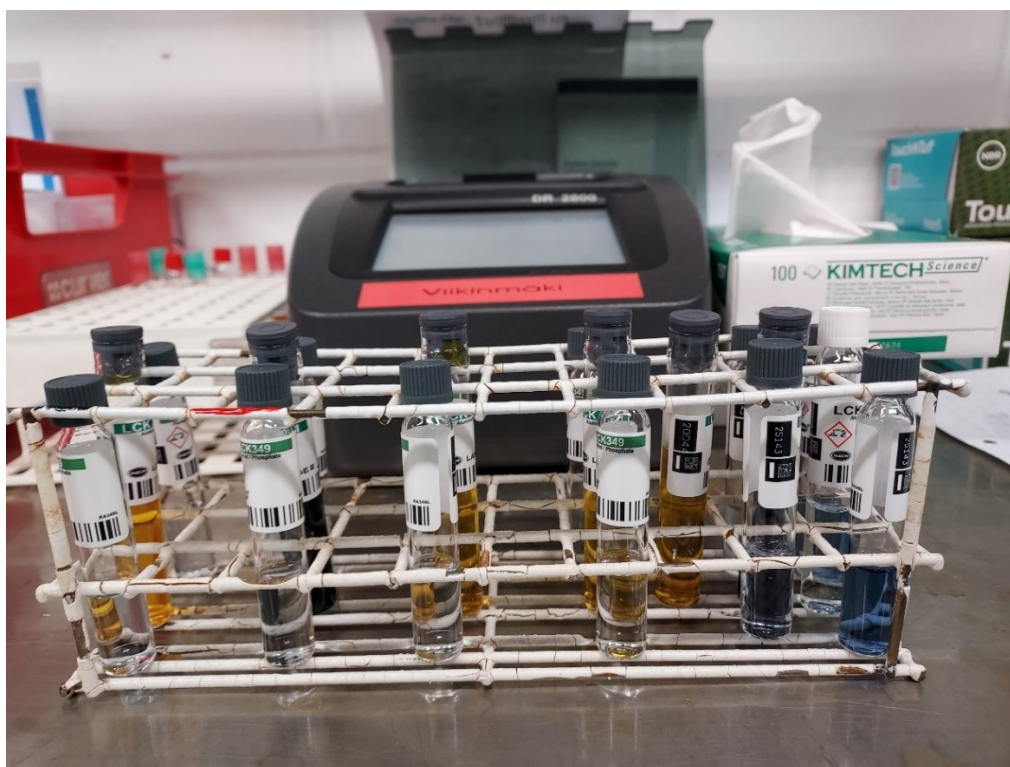


Figure 5. Hach's LCK cuvette tests in Viikinmäki laboratory. Hach DR 2800 spectrophotometer in the background.

To ensure the reliability of the cuvette tests, the accuracy of the analyses was verified at the accredited Metropolilab Oy laboratory. At the Metropolilab laboratory, analyses were performed in accordance with relevant ISO standards. TP was determined by inductively coupled plasma optical emission spectrometry (ICP-OES) following SFS-EN ISO 11885:2009. TSP was analysed by inductively coupled plasma mass spectrometry (ICP-MS) in accordance with SFS-EN ISO 17294-2:2023. TP and TSP analyses were preceded by acid digestion. PO₄-P was determined from a 0.45 µm filtered sample by discrete analysis (DA) and spectrophotometry according to SFS-EN ISO 15923-1:2024. Total and dissolved aluminium were determined by ICP-OES (SFS-EN ISO 11885:2009) or ICP-MS (SFS-EN ISO 17294-2:2023), depending on the applicable method detection limit. Total aluminium was determined after acid digestion and dissolved aluminium was determined from 0.45 µm filtered sample. TSS was determined by filtration through glass fibre filters according to SFS-EN 872:2005.

Micropollutants were analysed at Eurofins Environment Testing Finland Oy Lahti laboratory. The analysed micropollutants are presented in Appendix B. The micropollutants were analysed using the EPA method 1694:2007 for pharmaceuticals and personal care products in water. Samples were divided and spiked into acidic and basic fractions and extracted using solid-phase extraction. The extracts were then cleaned, concentrated and analysed by liquid chromatography and tandem mass spectrometry. The target compounds were detected in either positive or negative electrospray ionization. The compounds were identified by retention times and ion transitions compared with reference standards and quantified using isotope dilution or internal standard quantitation techniques (US EPA, 2007). The UV₂₅₄ absorbance was also measured at the Eurofins laboratory, using internal spectrophotometry method EF2044. Table 6 shows the summary of analytical methods used in this study, including the corresponding standards (SFS, 2024, 2023, 2009; Standard Methods For the Examination of Water and Wastewater, 2017; US EPA, 2007).

Table 6. Summary of analytical methods used in this study. Measurement uncertainties are reported for concentrations above the measurement limit.

Laboratory	Parameter	Measurement range	Measurement uncertainty or accuracy	Method / standard
Eurofins	Micropollutants	Appendix B	Appendix B	EPA 1694:2007
Eurofins	UV ₂₅₄	>0.001 UVA	-	Internal spectrophotometry method EF2044
Metropolilab	Al, dissolved	>0.003 mg/L Al; >0.1 mg/L Al	0.003-0.020: 50 %, >0.020: 20%	SFS-EN ISO 17294-2:2023 (ICP-MS); SFS-EN ISO 11885:2009 (ICP-OES)
Metropolilab	Al, total	>0.003 mg/L Al; >0.1 mg/L Al	20%	SFS-EN ISO 17294-2:2023 (ICP-MS); SFS-EN ISO 11885:2009 (ICP-OES)
Metropolilab	PO ₄ -P	>0.01 mg/L PO ₄ -P	20%	SFS-EN ISO 15923-1:2024 (DA)
Metropolilab	TSP	>0.05 mg/L P	20 %	SFS-EN ISO 17294:2023 (ICP-MS)
Metropolilab	TP	>0.05 mg/L P	20 %	SFS-EN ISO 11885:2009 (ICP-OES)
Metropolilab	TSS	>2 mg/L SS	10 %	SFS-EN 872:2005
Viikinmäki	Al, total	0.02–0.5 mg/L Al	95 % confidence interval: ±0.015 mg/L	Hach LCK301 cuvette test
Viikinmäki	PO ₄ -P	0.05–1.5 mg/L PO ₄ -P	95 % confidence interval: ±0.010 mg/L	Hach LCK349 cuvette test: ISO 6878-1-1986, DIN 38405 D11-4
Viikinmäki	TP	0.05–1.5 mg/L PO ₄ -P	95 % confidence interval: ±0.010 mg/L	Hach LCK349 cuvette test: ISO 6878-1-1986, DIN 38405 D11-4
Viikinmäki	UV ₂₅₄	0.001 UVA	± 0.5 FS	Internal spectrophotometry method adapted from standard 5910

In addition to the standard analyses presented in Table 6, the GAC samples collected at the start and end of the pilot campaign were examined at Aalto Water Laboratory to characterize their surface properties and phosphorus fractions. The activated carbon samples were examined using scanning electron microscopy (SEM, JIB-4700F, JOEL) at an accelerating voltage of 2 kV and a probe current of 10 pA. The samples were coated with 6 nm Au-Pd using Leica sputter coater (EM ACE600). The energy dispersive X-ray spectroscopy (EDS, Oxford instruments) detector was utilized for surface elemental analysis of the activated carbon at a probe current of 10 pA and an accelerating voltage of 10 kV.

Besides the SEM images, phosphorus fractionation of the GAC samples was carried out at Aalto Water Laboratory following a sequential extraction scheme adapted from the Standards, Measurement and Testing (SMT) protocol, originally developed and validated for sediment and sewage sludge samples (Bezák-Mazur and Ciopińska, 2020; Gonzalez Medeiros et al., 2005; Kumawat et al., 2022). As discussed in Section 2.3.1, phosphorus in wastewater exists in multiple fractions with different removal mechanisms. However, the phosphorus fractions presented in the literature section focus on WWTP influent, whereas the influent to the pilot-scale GAC columns represents Viikinmäki WWTP's treated effluent. Consequently, phosphorus fractions have already been substantially reduced through biological and chemical treatment, resulting in concentrations approaching analytical detection limits for conventional water-phase fractionation methods. Therefore, phosphorus fractionation was performed on the accumulated solids retained on the GAC media rather than in the water phase.

The fractionation scheme (Figure 6) was modified to distinguish phosphorus forms relevant to the combined coagulation and GAC filtration system: phosphorus bound to aluminium (representing PAX coagulation in the pilot), phosphorus bound to iron (representing carryover from Viikinmäki WWTP's Fe-based phosphorus removal), inorganic phosphorus (representing the sum of reactive phosphorus that has been converted to metal-phosphorus complexes through coagulation), and organic phosphorus (representing non-reactive, refractory organic phosphorus). Although the fractionation scheme presents all fractions in a single diagram, each fraction requires its own sample preparation procedure, as a single sample does not provide sufficient volume for all fraction determinations. Therefore, separate 0.2 g GAC samples were prepared for each fraction analysis. TP was also measured to validate the mass balance of the sequential extraction. This application of SMT fractionation to GAC media is experimental, extending the methodology beyond its original sediment and sludge matrices to characterize phosphorus retention mechanisms in GAC media.

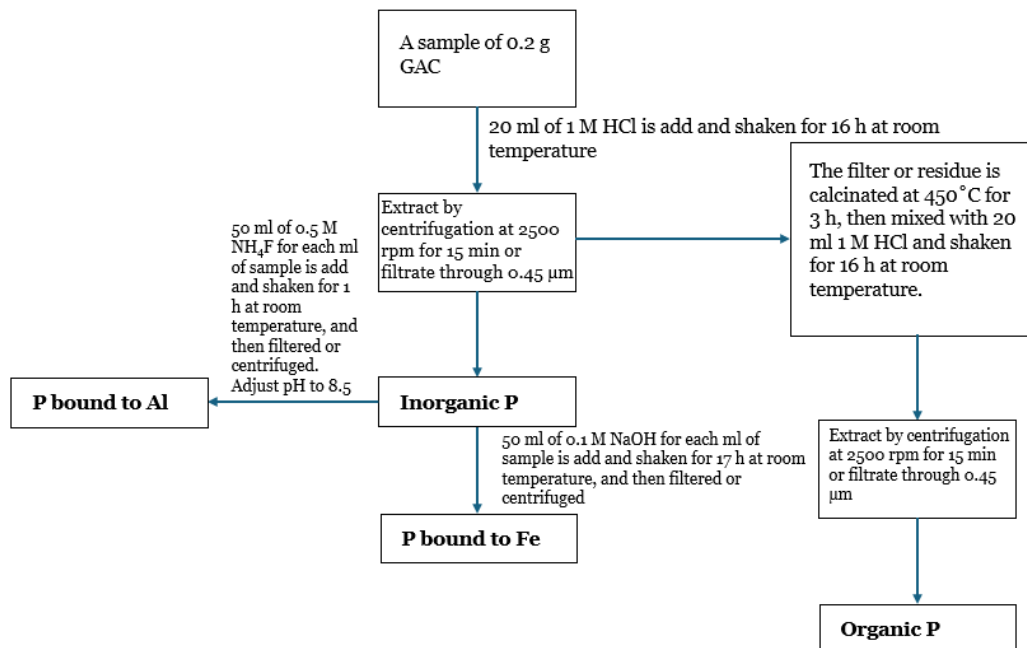


Figure 6. Phosphorus fractionation scheme at Aalto Water laboratory (adapted from Bezak-Mazur and Ciopińska, 2020; Gonzalez Medeiros et al., 2005; Kumawat et al., 2022). Note: This application of SMT fractionation to GAC media is experimental, extending the methodology beyond its original sediment and sludge matrices to characterize phosphorus retention mechanisms in GAC media.

3.3 Laboratory-scale experiments

Laboratory-scale experiments were conducted prior to pilot-scale operation to optimize process parameters for phosphorus removal and mitigate operational risks associated with chemical addition, such as filter clogging. The laboratory setup enabled testing of different PAX dosages and assessment of GAC filter performance with significantly lower resource requirements than pilot-scale testing. Additionally, the laboratory column allowed for easier GAC replacement and process modifications between measurement campaigns. The laboratory experiments consisted of flocculation jar tests (Section 3.3.1) to determine appropriate PAX dosing ranges, followed by laboratory-scale column experiments (Sections 3.3.2 and 3.3.3) to evaluate phosphorus removal performance and hydraulic characteristics of the GAC filter under chemical addition. The results provided the basis for pilot-scale operation.

3.3.1 Flocculation jar tests

Flocculation jar tests were conducted using Kemira's Flocculator 2020 apparatus to optimise PAX dosage for enhanced phosphorus removal (Figure 7). The objective was to determine the optimal molar ratio of aluminium to $\text{PO}_4\text{-P}$ ($\text{Al}:\text{PO}_4\text{-P}$) required for flocculation prior to GAC filtration, with the aim of achieving a TP concentration below 0.1 mg/L.

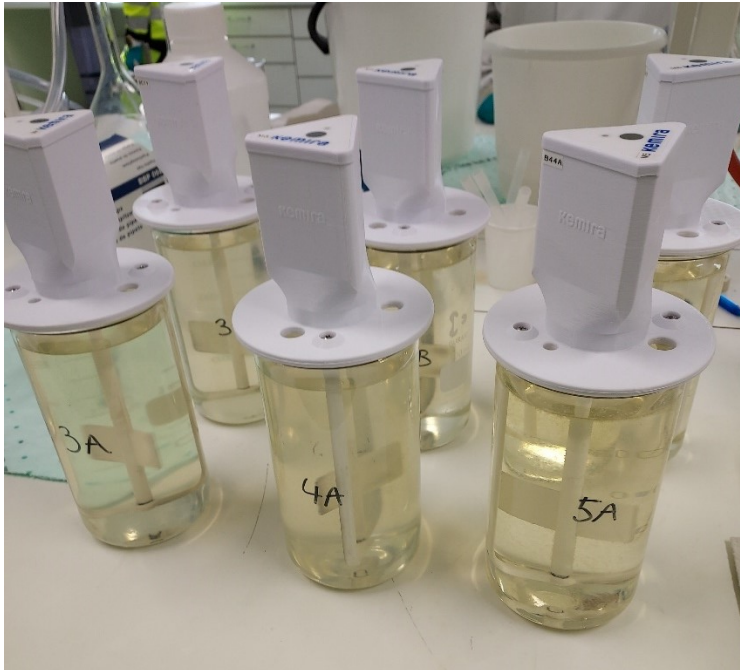


Figure 7. Flocculation jar tests.

The jar tests were performed using the effluent from the Viikinmäki wastewater treatment plant. The effluent was collected as a 10-litre grab sample using a Masterflex peristaltic pump attached next to the plant's effluent sampler. The jar tests were performed in three separate experiments on 23 March, 22 April and 23 April. In each jar test, eight 1 litre glass beakers were used, corresponding to four $\text{Al}:\text{PO}_4\text{-P}$ molar ratios tested, each in duplicate. One litre of effluent was placed in each beaker, after which PAX (Kemira PAX-XL100) was pipetted into the beaker. PAX was pipetted at the start of rapid mixing to ensure proper dispersion of the coagulant. PAX was prepared as a 100-fold or 1000-fold dilution or as an undiluted solution, depending on the volume of PAX to be pipetted (Table 7). The volume of PAX to be pipetted was determined by the selected $\text{Al}:\text{PO}_4\text{-P}$ molar ratios, using the $\text{PO}_4\text{-P}$ concentrations in the Viikinmäki effluent measured by Hach's Phosphax online phosphate analyzer. As the jar test samples were grab samples, the $\text{PO}_4\text{-P}$ concentration measured at the time of sampling was used to determine the concentration of PAX. As can be seen from Table 7, both the targeted and actual molar ratios are presented for the jar tests. This is due to

a malfunction in the Phosphax analyzer during the jar test experiments, which lead to incorrect estimation of PO₄-P concentrations. Therefore, the actual molar ratios are based on the PO₄-P concentration in the Viikinmäki effluent measured using Hach cuvette tests and aluminium concentrations measured in Metropolilab. TSP results from Metropolilab were also used for assessing the reliability of the PO₄-P concentrations derived from cuvette test results. The aluminium concentration in PAX-XL100 is reported to be 129.27 g Al/L.

Table 7. Targeted and actual PO₄-P molar ratios and corresponding amounts of PAX pipetted in the jar tests.

Targeted molar ratio, Al:PO₄-P	Actual molar ratio, Al:PO₄-P	PO₄-P in the Viikinmäki effluent	Dilution	PAX pipetted (mL/L)
3	2	0.05	1000	0.8
4	3; 6	0.05; 0.10	1000; 100	1.1; 0.4
5	4	0.05	1000	1.4
6	5; 9	0.05; 0.10	1000; 100	1.6; 0.6
10	13	0.11	100	1
20	27	0.11	100	2
30	40	0.11	undiluted	0.03
60	81	0.11	undiluted	0.06

The mixing sequence consisted of a rapid mixing phase (10 seconds at 400 RPM) followed by a slow mixing phase (10 minutes at 40 RPM) and a settling phase of 20 minutes. After the settling phase, samples were collected from the supernatant and analysed for TP, TSP and PO₄-P, and total and dissolved aluminium. Duplicate blank samples of the Viikinmäki effluent was also analysed. Laboratory analyses for TP and PO₄-P were determined in the Viikinmäki laboratory by using Hach Lange cuvette tests. Analyses for TP and TSP, as well as total and dissolved aluminium were determined at Metropolilab Oy.

Since the mixing time and intensity cannot be adjusted in the laboratory- and pilot-scale columns (explained more in detail in Section 5.2), these parameters were not optimised in the flocculation jar tests. Instead, the slow mixing time in the jar tests was intentionally kept short (10 minutes), based on the assumption that mixing in the laboratory- and pilot-scale configurations will not occur at an optimal rate. Moreover, when combined with GAC filtration, coagulation and flocculation are not fully comparable to the conditions in the jar tests, as there will not be a rapid mixing phase or a settling phase. Therefore, the aim was to determine a molar ratio that could be used as a starting point for assessing phosphorus removal in both laboratory- and pilot-scale columns.

3.3.2 Laboratory-scale column

The laboratory-scale column was constructed from a single polyvinyl chloride (PVC) pipe with an internal diameter of 67 mm and height of 100 cm. The base of the column was manufactured by Vink Finland Oy, while the assembly of the filter was completed in-house. The GAC bed depth was set to 60 cm, and a metal mesh was installed at the bottom of the column to prevent carbon loss. The column was operated as a fixed-bed downflow filter with a flow of 100 mL/min, corresponding to an EBCT of 21 minutes and a HLR of 1.7 m/h. Summary of key operating parameters is shown in Table 8.

Table 8. Summary of key operating parameters of the laboratory column.

Parameter	Unit	Value
Diameter	cm	6.7
Surface	cm ²	35
Q	L/h	6
EBCT	min	21
HLR	m/h	1.7
GAC bed depth	cm	60
GAC volume	dm ³	2.1

The filter was backwashed when approximately 20 cm of head loss was exceeded in the water level above the GAC bed. The backwash consisted of air scour for 1–2 minutes, followed by water wash for 15–20 minutes. The backwash water and air were supplied from the bottom of the column, and the backwash effluent was discharged through an overflow outlet. The water used for backwash was tap water due to laboratory restrictions, whereas in the pilot-scale columns the backwash water was supplied from the pilot influent. The backwash air was provided from the pressurised air supply in the laboratory.

The laboratory column influent was collected as a 50 L grab sample from the Viikinmäki effluent channel using a Masterflex peristaltic pump. The influent was then pumped into the column using a Heidolph peristaltic pump with a flow of 100 mL/min. When the column was operated without chemical dosing, the influent was pumped directly into the column. When operated with PAX dosing (Kemira PAX-XL100), a 6 L water tank was installed upstream of the laboratory column to serve as a flocculation tank. The tank was equipped with Velp Scientifica overhead stirrer, and PAX was pumped directly into the tank using a Watson-Marlow peristaltic pump. The water flowed gravitationally into the GAC column through an overflow outlet installed at a water level corresponding to approximately 3 L. This resulted in an HRT of about 30 minutes of slow mixing. The laboratory setup did not

include a separate rapid mixing or settling phase. The flow diagram of the laboratory column is presented in Figure 8 and the laboratory column setup is shown in Figure 9.

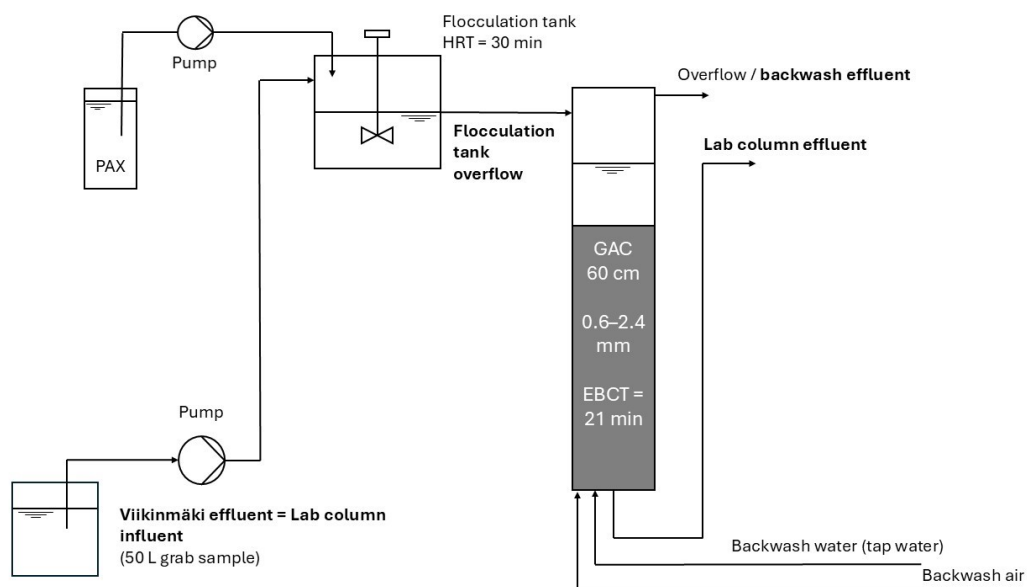


Figure 8. Flow diagram of the laboratory-scale column. Sampling points are marked in bold.



Figure 9. Laboratory column setup.

3.3.3 Laboratory measurement campaigns

Two measurement campaigns were conducted with the laboratory column in June–July 2025 and July–August 2025 to study the effect of chemical dosing on GAC filtration and to test different chemical dosages prior to the pilot-scale campaign. It was assumed that modifying the chemical dosage and replacing the GAC between measurement campaigns would be considerably easier in the laboratory than in the pilot setup. The laboratory campaign also served to mitigate potential issues in the GAC filter, such as clogging associated with chemical dosing. The primary objective was therefore to optimize the PAX dosage for the pilot-scale column and to ensure stable operating conditions during the pilot campaign. In addition, the measurement campaigns aimed to investigate the scalability of phosphorus removal between the laboratory- and pilot-scale columns, thereby enabling an assessment of how the pilot-scale results could later be applied to full-scale operation. The operating parameters of the laboratory column (Table 8) were kept as similar as possible to those of the pilot-scale columns (Table 10).

The first campaign lasted for 10 days between 16 June and 17 July. Prior to the campaign, the carbon was soaked in water for three days. The laboratory column was not operated daily, as operation was intermittently paused while awaiting laboratory analysis results. The column was operated only during working hours. In total, the column was operated for 46 hours during the first campaign, corresponding to approximately 130 BVs. The first seven days (~90 BV) of the June–July campaign were conducted without chemical dosing, operating the column with water only. During the last three days of the campaign, three Al:PO₄-P molar ratios (20, 40 and 60) were tested, each for one day (~10–20 BVs). These molar ratios were selected based on the jar tests to identify a suitable ratio for the initial chemical dosing. In addition, the tests were used to verify the functionality of the chemical dosing system and the hydraulic performance of the filter prior to the second measurement campaign, which was conducted with continuous chemical dosing. For each laboratory column test, PAX was prepared as a 100-fold dilution.

The second measurement campaign lasted for 8 days between 23 July and 1 August. The GAC was replaced between the two measurement campaigns and soaked in water for four days before the measurements. Similarly to the first measurement campaign, the filter was not operated every day and only during working hours. During the second campaign, the column was operated for 45 hours in total, corresponding to approximately 128 BVs. The PAX was dosed at an Al:PO₄-P molar ratio of 20, based on the results from the jar tests and the first measurement campaign. The required PAX dose was calculated based on the PO₄-P concentration of the Viikinmäki effluent

measured by the Phosphax online analyzer. Since the laboratory influent was collected as a 50 L grab sample, the PO₄-P concentration measured at the time of sampling was used to determine the concentration of PAX for each measurement day. The operational parameters of both measurement campaigns are presented in Table 9.

Table 9. Summary of laboratory measurement campaigns.

Parameter	First measurement campaign	Second measurement campaign
Dates	16.6.–17.7.2025	23.7.–1.8.2025
Total bed volumes	130 BVs	128 BVs
Total operating time	46 h	45 h
Total water treated	276 L	270 L
Operation without chemical dosing	32 h (90 BVs)	-
Chemical operation	14 h (40 BVs)	45 h (128 BVs)
Chemical dosing strategy	tested three molar ratios at the end of the campaign, each for 10–20 BVs	full-time
Molar ratio	20, 40 and 60 mol Al:mol PO ₄ -P	20 mol Al:mol PO ₄ -P
Average PAX dosage (minimum– maximum)	0.15 ml/min (0.063–0.24 ml/min)	0.10 ml/min (0.09–0.12 ml/min)

Laboratory analyses for both campaigns included Hach cuvette tests for TP, PO₄-P, and aluminium conducted at the Viikinmäki laboratory, as well as TP and TSP, and aluminium analyses performed at the Metropolilab laboratory. UV₂₅₄ absorbance was measured at the Viikinmäki laboratory. During both campaigns, cuvette tests were performed every 10–20 BVs and samples were sent to Metropolilab at intervals of 10–15 BVs. UV₂₅₄ was measured every 10–20 BVs. These sampling intervals correspond to 19 sampling events in the first campaign and 16 sampling events in the second campaign. Each sampling event consisted of 2–3 sampling points and up to seven analyses. Sampling points of the lab column are presented in Figure 8 and sample preparation in Appendix C.

3.4 Pilot-scale experiments

Pilot-scale experiments were conducted to validate laboratory findings under technical-scale conditions using two parallel GAC columns – one with chemical coagulation (PAX-GAC) and one without (GAC), enabling direct comparison of treatment performance. The pilot campaign was operated over a longer period than the laboratory experiments to evaluate process stability. While micropollutant removal was monitored during the pilot-scale experiments, the primary focus remained on phosphorus removal performance. The pilot-scale setup (Section 3.4.1) and measurement campaign (Section 3.4.2) are described in the following sections.

3.4.1 Pilot-scale columns

The GAC pilot consists of two identical filter columns, each with a diameter of 0.25 m and a height of 5.5 m, with GAC bed height of 2 m (Figure 10). Both columns were operated as fixed-bed downflow filters and equipped with filter nozzles to retain the GAC media from the filtrate. The pilot was constructed using PVC and steel components and a protective steel structure. The pilot was originally purchased from Teollisuuden Vesi Oy and installed at the Viikinmäki WWTP in 2021 as part of the CWPharma 2 project to study the removal of active pharmaceutical ingredients (APIs) and other micropollutants (Kuokkanen and Stapf, 2021). For this study, the pilot was modified on-site to enable combined chemical coagulation and GAC filtration for enhanced phosphorus removal.



Figure 10. Viikinmäki GAC pilot.

Chemical coagulation with PAX was implemented upstream of one of the GAC columns (PAX-GAC column), while the other column (GAC column) serves as a reference line without chemical dosing. For the coagulant dosing, a 300 L intermediate bulk container (IBC) was installed upstream of the PAX-GAC column to serve as the flocculation tank. The IBC tank was equipped with a Mamec Oy container mixer to ensure proper mixing of PAX, which was pumped directly into the tank using a Grundfos DDA dosing pump. The flocculation tank (Figure 11) was positioned at a higher elevation than the PAX-GAC column for gravitational flow. The outlet of the tank was located at the bottom of the container, and the water level inside the tank was regulated by the positioning of the outlet pipe. The water level was adjusted to approximately 125 l, corresponding to a hydraulic retention time of about 33 minutes for slow mixing. There was no separate rapid mixing phase in the pilot setup, discussed more in detail in Section 5.2.



Figure 11. Flocculation tank.

To maintain constant influent feed for both columns, two Zuwa Combistar impeller pumps were installed. The pumps were operated via Kostal Inveor variable frequency drives (VFDs), which allow regulation of pump speed and flow. Both columns were equipped with rotameters to monitor the flow rates from the influent pumps. The pilot influent water was supplied from the pressurized Viikinmäki technical water network, which distributes effluent water from the wastewater treatment plant. A pressure-reducing valve was installed upstream of the influent pumps to reduce the network pressure from around 5 bar to 1.5 bar, thereby preventing excessive pressure on the suction side of the pumps. A dedicated gauge for monitoring water pressure

was not installed, but the pilot setup included pressure gauge for the air used in backwashing. The air for backwashing was supplied from the plant's pressurised air network. The pilot was operated manually. The pilot flow diagram is presented in Figure 12.

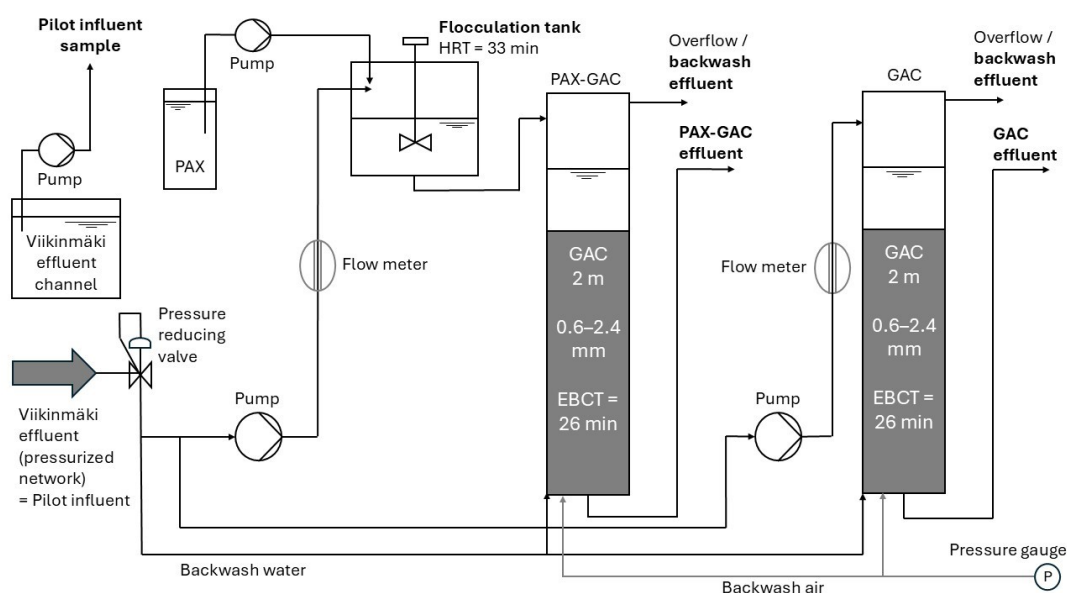


Figure 12. Flow diagram of the pilot-scale columns. Sampling points are marked in bold.

The EBCT was 26 minutes with a design flow of 230 L/h. The columns were not operated continuously, but only during working hours, corresponding to around 6–7 h of operation per day. Consequently, as the columns were backwashed every second day, the backwash interval corresponded to around 12 h of operation. The backwash consisted of air scour at 0.5 bar for 1–2 minutes, followed by water wash at 1.5 bar for 15–20 minutes. Summary of the key operating parameters is shown in Table 10. The operating parameters were selected based on the GAC manufacturer's design specifications (Appendix A), literature values presented in Section 2.2.7, and earlier results from Viikinmäki WWTP pilot study (Kuokkanen and Stapf, 2021).

Table 10. Summary of key operating parameters of the pilot columns.

Parameter	Unit	Value
Diameter	m	0.25
Surface	m ²	0.05
Q	L/h	230
EBCT	min	26
HLR	m/h	4.7
GAC bed depth	m	2
GAC volume	m ³	0.1

3.4.2 Pilot measurement campaign

One measurement campaign was conducted with the pilot-scale GAC columns at Viikinmäki WWTP in July–October 2025 to study the effect of chemical coagulation on phosphorus and micropollutant removal under technical scale operating conditions. The pilot campaign was operated based on the results from the laboratory-scale experiments, which provided initial estimates for suitable PAX dosage and flocculation time. Other operating parameters, presented in Table 10, were based on literature values or selected due to technical limitations. These technical limitations are discussed in more detail in Section 5.2. The primary objective of the pilot campaign was to verify that the laboratory results on chemical dosing were also valid at a larger scale and to evaluate the effect of coagulation on filter performance using two parallel columns. In addition, the pilot campaign was conducted over a longer period of time than the laboratory campaigns, which were originally intended for short-term process verification rather than long-term operation.

The pilot campaign lasted for 45 days between 4 July and 1 October. The pilot columns were operated for 250 hours in total, corresponding to approximately 600 BVs. The GAC used was from the same regenerated batch (8x30 mesh) from Vanhakaupunki water treatment plant as in the laboratory column tests, and the GAC was pre-soaked in water for five days before the pilot campaign. In the first 130 hours of operation (~330 BVs), both columns were operated without chemical dosing to ensure that the hydraulic capacity and performance of the parallel columns were comparable. Therefore, the pilot campaign consisted of two operational phases: the baseline operation phase without chemical dosing (0–330 BVs), when both columns operated without chemical dosing, and the chemical dosing phase (330–600 BVs), when PAX was dosed to the PAX-GAC column (while the GAC column continued to operate without chemical addition throughout the whole pilot campaign). At 280 BVs, there were some issues with the influent pumps due to a failure of the pressure-reducing valve, after which the flow rate of the

GAC column influent pump increased to 250 L/h and remained at that level until the end of the measurement campaign. Therefore, the GAC column has been receiving slightly higher flow rates than the design flow of 230 L/h to the PAX-GAC column. This has a small effect on the BVs of the GAC column, which reached approximately 10–20 higher BVs during the pilot campaign than the PAX-GAC column. However, the results are presented at the same BVs, as the BVs are theoretical estimates and have been rounded to the nearest five. The summary of pilot measurement campaign is presented in Table 11.

Table 11. Summary of pilot measurement campaign.

Parameter	PAX-GAC column	GAC column
Total bed volumes	600 BVs	620 BVs
Total operation time	248 h	248 h
Total water treated	59 m ³	62 m ³
Operation without chemical dosing	133 h (330 BVs)	248 h (620 BVs)
Chemical operation	115 h (270 BVs)	-
Molar ratio	20 mol Al:mol PO ₄ -P	-
Average PAX dosage (minimum – maximum)	180 ml/h (62–341 ml/h)	-
Average PO ₄ -P concentration in the Viikinmäki effluent	0.06 mg/L (0.02–0.11 mg/L)	-

Laboratory analyses for the pilot campaign included Hach cuvette tests for TP, PO₄-P, and aluminium conducted at the Viikinmäki laboratory, as well as TP, TSP, and PO₄-P analyses performed at the Metropolilab laboratory. TSS was also analysed at Metropolilab. UV₂₅₄ absorbance was determined at the Viikinmäki laboratory. In addition, samples were sent to the Eurofins laboratory for micropollutant analysis, and UV₂₅₄ was also measured at the Eurofins for result verification. Phosphorus, aluminium and TSS analyses were conducted every 50–100 BVs either at the Viikinmäki laboratory or at Metropolilab Oy. Correspondingly, UV₂₅₄ was measured every 50–100 BVs at the Viikinmäki laboratory. For micropollutant analysis, there were six sampling events between 7 August and 1 October (320–600 BVs of pilot operation). Micropollutant samples were collected at 1–2-week intervals, corresponding to approximately 70–100 BVs between each sampling events. The sampling points of the pilot are presented in Figure 12 and sample preparation in Appendix D.

4 Results

This chapter presents the experimental results from flocculation jar tests, laboratory-scale column experiments, and pilot-scale column experiments. The results are divided into two main sections: phosphorus removal performance (Section 4.1) and micropollutant removal (Section 4.2). The primary focus of this study was on phosphorus removal, which was investigated at both laboratory- and pilot-scale experiments, while micropollutant removal was studied only at pilot-scale to verify that GAC adsorption capacity was maintained during chemical addition.

4.1 Phosphorus removal

Phosphorus removal was investigated at both laboratory- and pilot-scale to evaluate the feasibility of combined PAX coagulation and GAC filtration. The results progress from flocculation jar tests for PAX dose optimization (Section 4.1.1) to laboratory-scale experiments (Section 4.1.2) and finally to pilot-scale performance (Sections 4.1.3 and 4.1.4). Additional analyses including phosphorus fractionation (Section 4.1.5), hydraulic performance (Section 4.1.6), and residual aluminium (Section 4.1.7) are also presented for the pilot-scale columns.

4.1.1 Flocculation jar tests

The flocculation jar tests were conducted to determine an appropriate coagulant dose for achieving an effluent TP concentration of 0.1 mg/L combined with GAC filtration. The primary objective of the jar tests was to determine an initial PAX dose for the laboratory-scale GAC column. Figure 13 presents the resulting TP, TSP and PO₄-P concentrations in the jar test supernatants as a function of Al:PO₄-P molar ratio. As can be seen from Figure 13, all parameters decreased with increasing molar ratios, demonstrating effective coagulation and floc formation. The decline in TP concentration showed an almost exponential trend, with a rapid decrease after an Al:PO₄-P molar ratio of 10. Initial molar ratios of 4–5 Al:PO₄-P, which are commonly reported in literature for Al- or Fe-salts (Altmann et al., 2016b; Locher and Blind, 2024; Sauter et al., 2021; STOWA, 2023), were found to be inadequate under the present conditions, probably due to the very low phosphorus concentrations in the Viikinmäki effluent. In recent studies combining phosphorus removal with GAC filtration, the influent concentrations to combined pilot-scale processes have usually been reported between 0.2 and 0.6 mg/L TP, which is considerably higher than the average Viikinmäki effluent concentration of 0.19 mg/L (Altmann et al., 2016b; Locher and Blind, 2024; Sauter et al., 2021; STOWA, 2023).

The target level of 0.1 mg/L TP was achieved within the range of 20–30 Al:PO₄-P molar ratio, after which the removal efficiency improved only gradually. Figure 13 also shows a decrease in PO₄-P and TSP concentrations at around 20–30 molar ratios, indicating that soluble phosphorus fractions were effectively converted into particulate form through coagulation and floc formation. At the lowest molar ratios, PO₄-P concentrations appeared slightly lower than expected, which may result from the initially low PO₄-P concentrations combined with the analytical uncertainty associated with measurements near detection limit levels.

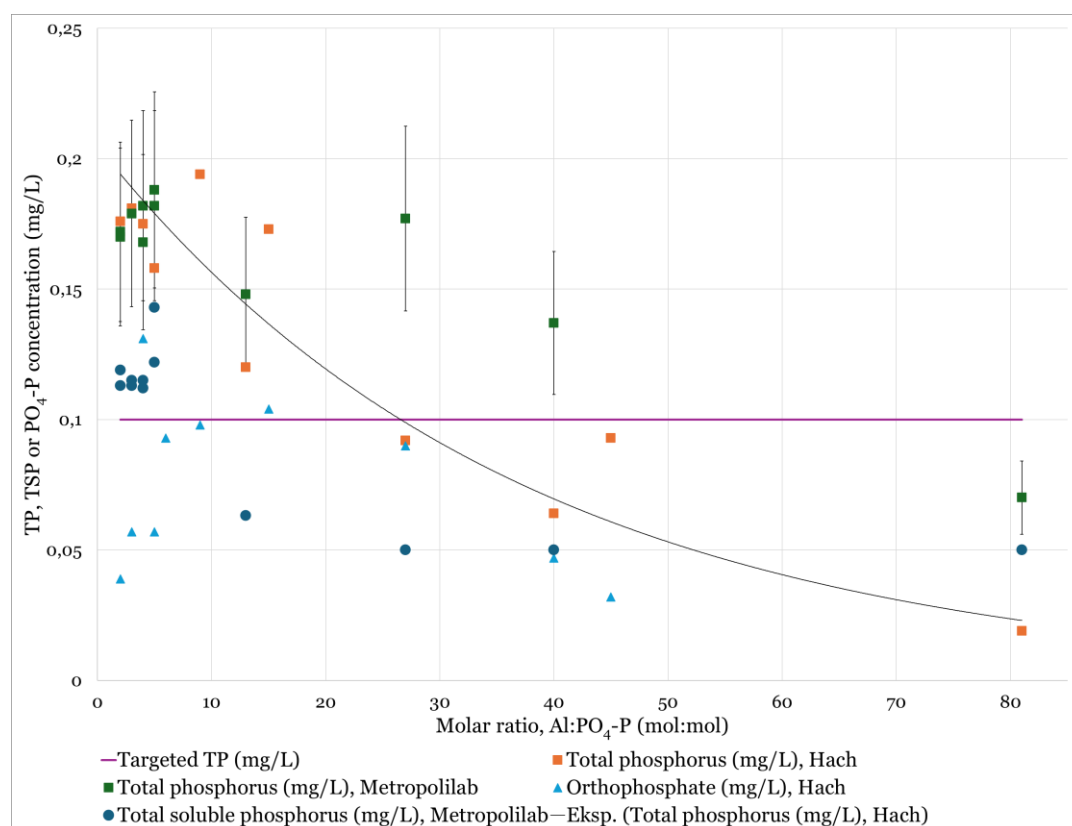


Figure 13. Total phosphorus, total soluble phosphorus and orthophosphate concentrations in the jar test supernatants as a function of Al:PO₄-P molar ratio.

The phosphorus concentrations were analysed both in the Viikinmäki laboratory using Hach cuvette tests and at Metropolilab Oy. For the TP concentrations analysed at Metropolilab, a measurement uncertainty of 20 % is shown in error bars in Figure 13. Uncertainty of 20 % is also reported for TSP concentrations analysed at Metropolilab. For the Hach TP and PO₄-P measurements, 95 % confidence interval of ±0.010 mg/L has been reported. In Metropolilab, the measured TP concentrations were consistently higher than the corresponding Hach cuvette test results. This difference was likely

due to the sampling method. When sending the sample to Metropolilab, a 100 mL supernatant sample was collected from a 1000 mL beaker, and some flocs may have been unintentionally included. Since Metropolilab routinely shakes the samples prior to analysis, these flocs may have been resuspended, resulting in elevated TP concentrations. In Viikinmäki laboratory, the supernatant sample (2 mL for each cuvette test) was collected directly from the supernatant layer and analysed immediately after sampling, minimizing the possibility of floc resuspension or sample alteration.

Figure 14 shows the TP reduction as a function of Al:PO₄-P molar ratio, based on both Hach cuvette tests and Metropolilab analyses. The figure also shows the targeted TP reduction, calculated from the target effluent concentration of 0.1 mg/L. The targeted reduction values vary between jar tests, as the tests were conducted on different days and influent phosphorus concentrations fluctuated between the tests. As shown in Figure 14, the required TP reduction corresponding to the 0.1 mg/L target was achieved only at molar ratios over 20. The effective reduction trend becomes evident at higher coagulant dosages, indicating that lower ratios were insufficient for achieving the targeted 0.1 mg/L TP concentration. Even negative reductions were shown for low molar ratios, which fall within analytical uncertainty, indicating no actual increase in TP concentration.

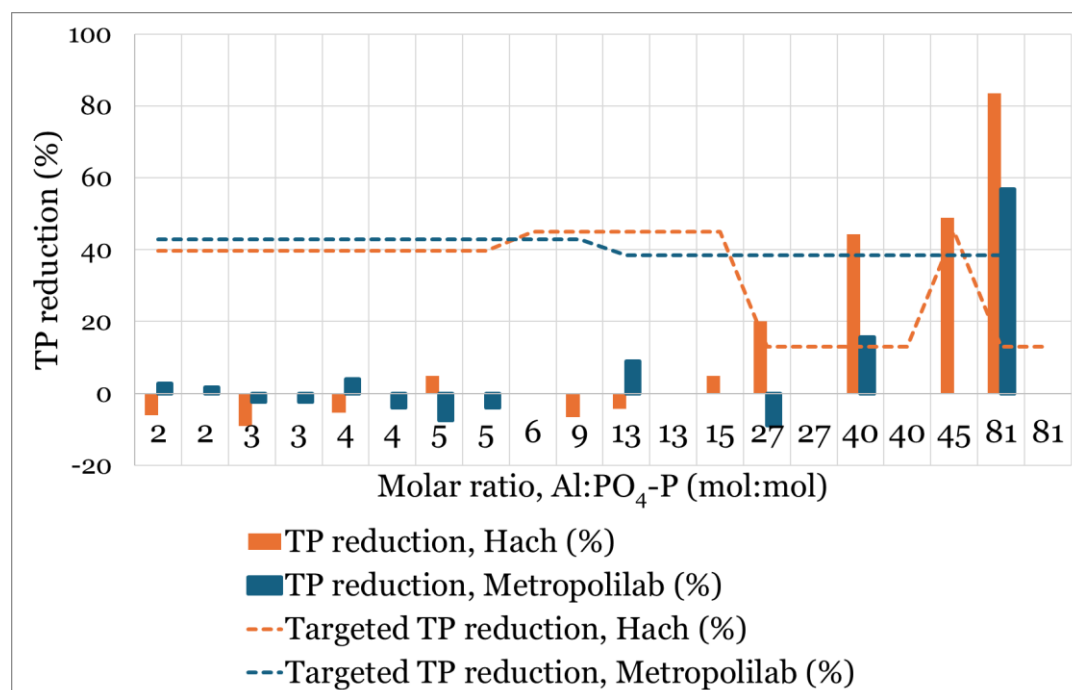


Figure 14. Total phosphorus reduction in the jar test supernatants as a function of Al:PO₄-P molar ratio.

Visible floc formation was also observed at around 20–30 molar ratios. Based on the jar test results, higher molar ratios were not considered beneficial, as additional coagulant dosing would provide only marginal improvement while potentially affecting the hydraulic properties of the GAC filter, such as increased clogging tendency. Therefore, the following laboratory column experiments were initiated with a 20 Al:PO₄-P molar ratio, representing the lowest PAX dose capable of achieving the desired TP concentration. This coagulant dose was chosen with the assumption that the GAC filtration step will further enhance TP removal. In addition, excessive coagulant dosing could lead to the formation of large, dense flocs, which are not desirable as they may increase the risk of filter clogging. Therefore, selecting a lowest possible PAX dose would provide a robust operating point for evaluating the integrated coagulation and GAC filtration process, providing both efficient phosphorus removal and stable filter operation under practical conditions.

It should be noted that the presented molar ratios in the jar test results are calculated values derived from Hach cuvette tests and Metropolilab analyses. During the jar tests, there were technical issues with the Viikinmäki Phosphax analyzer and unsuitable refrigerator temperatures, as the PO₄-P concentration appeared to be higher than in reality. The issue with the analyzer was later confirmed, and the analyzer's reagent refrigerator was replaced. For example, in the test corresponding to a nominal molar ratio of 27, the intended target molar ratio was 20. However, based on the results, Al:PO₄-P molar ratio of 20 was selected as the starting point for the laboratory-scale column tests. This approach was considered appropriate since molar ratios are always theoretical estimates, unless the influent PO₄-P concentration is precisely verified in the feed solution prior to dosing.

4.1.2 Laboratory-scale column performance

The first laboratory-scale measurement campaign was initially operated without chemical dosing for 7 days (~90 BVs), to establish a baseline for phosphorus removal efficiency and to verify the hydraulic performance of the filter. Operation without chemical dosing is referred to as GAC, and the chemical operation is referred to as PAX-GAC.

The GAC filter achieved the target effluent concentration of <0.1 mg/L TP consistently across all sampling events during the first measurement campaign (Figure 15). During the first campaign, duplicate samples were analysed by two different laboratories, Metropolilab using ISO standards and Viikinmäki laboratory using Hach cuvette tests (referred to as Hach). Duplicate samples were taken to validate measurement accuracy, resulting in multiple data points for individual BVs. As can be seen in Figure 15, the overall accuracy for duplicate samples showed consistent results, therefore,

in the following measurement campaigns, duplicate samples were only taken for occasional accuracy tests.

The laboratory column influent (Viikinmäki effluent) TP concentration averaged 0.14 mg/L. Both influent and effluent TP concentrations were determined by Hach cuvette tests and Metropolilab analyses, with paired samples analysed using the same method (either Hach or Metropolilab) for each sampling event. The effluent TP concentrations averaged 0.05 mg/L, which is well below the target limit of 0.1 mg/L. Phosphorus removal efficiency averaged 65 %, demonstrating stable and effective reduction despite variations in influent concentration. Both analytical methods showed good agreement, with Metropolilab reporting an average TP measurement uncertainty of 20 %, and Hach reporting a 95 % confidence interval of ± 0.010 mg/L for the LCK349 phosphorus cuvette test.

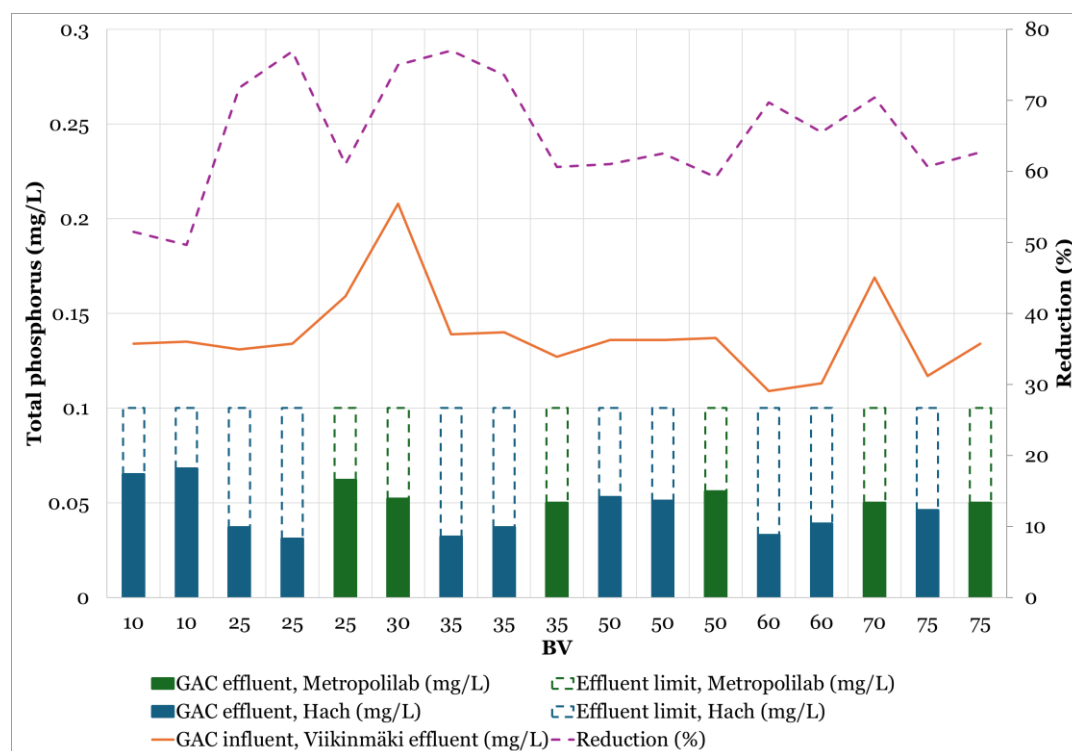


Figure 15. Total phosphorus concentrations and reductions in GAC filter (operation without chemical dosing) during the first laboratory measurement campaign.

For $PO_4\text{-P}$, the influent concentration averaged 0.06 mg/L, and the GAC effluent 0.01 mg/L, corresponding to an average $PO_4\text{-P}$ removal efficiency of 79 %. Additionally, the GAC filter achieved excellent UV_{254} reduction averaging 99 %. Low head loss of 4.4 cm on average was maintained in the filter, and there was no need for filter backwash during the first measurement

campaign. Table 12 presents all average values along with their respective minimum and maximum values.

After 90 BVs of operation without chemical dosing, molar ratios of 20, 40 and 60 were tested, each for 1 day (~10–20 BVs) to assess whether there would be any unexpected changes to GAC filter operation during chemical dosing. Due to the short duration of these initial PAX dosing tests, phosphorus removal performance was not evaluated at this stage. During chemical dosing, head loss gradually increased from around 5 cm to 10 cm. However, no significant clogging of the filter was observed during this 3-day preliminary test period. Based on these results, continuous chemical dosing operation could be started. The GAC media was replaced before the second measurement campaign.

The second measurement campaign was operated with continuous coagulant dosing to evaluate the combined chemical coagulation and GAC filtration (PAX-GAC) and its effect on phosphorus removal. In the second campaign, the filter was dosed with PAX in a molar ratio of 20 mol Al: PO₄-P, corresponding to an average PAX dose of 0.10 ml/min (100-fold dilution). Compared with the first campaign, the influent TP concentrations were higher, averaging 0.18 mg/L. Again, both influent and effluent TP concentrations were determined by Hach cuvette tests and Metropolilab analyses, with paired samples analysed using the same method for each sampling event. The PAX-GAC effluent TP concentrations remained well below the 0.1 mg/L limit across all sampling events (Figure 16), averaging 0.06 mg/L. The corresponding average TP reduction was 67 %, which is comparable to TP reduction in the GAC-only campaign (65 %). Although a higher number of BVs (120 BV) was treated during the second campaign, fewer sampling points were collected. Duplicate samples were not considered necessary, as this campaign served primarily as short-term process configuration test to confirm the hydraulic stability of the GAC filter under PAX dosing and to evaluate the effect of coagulation on phosphorus removal performance.

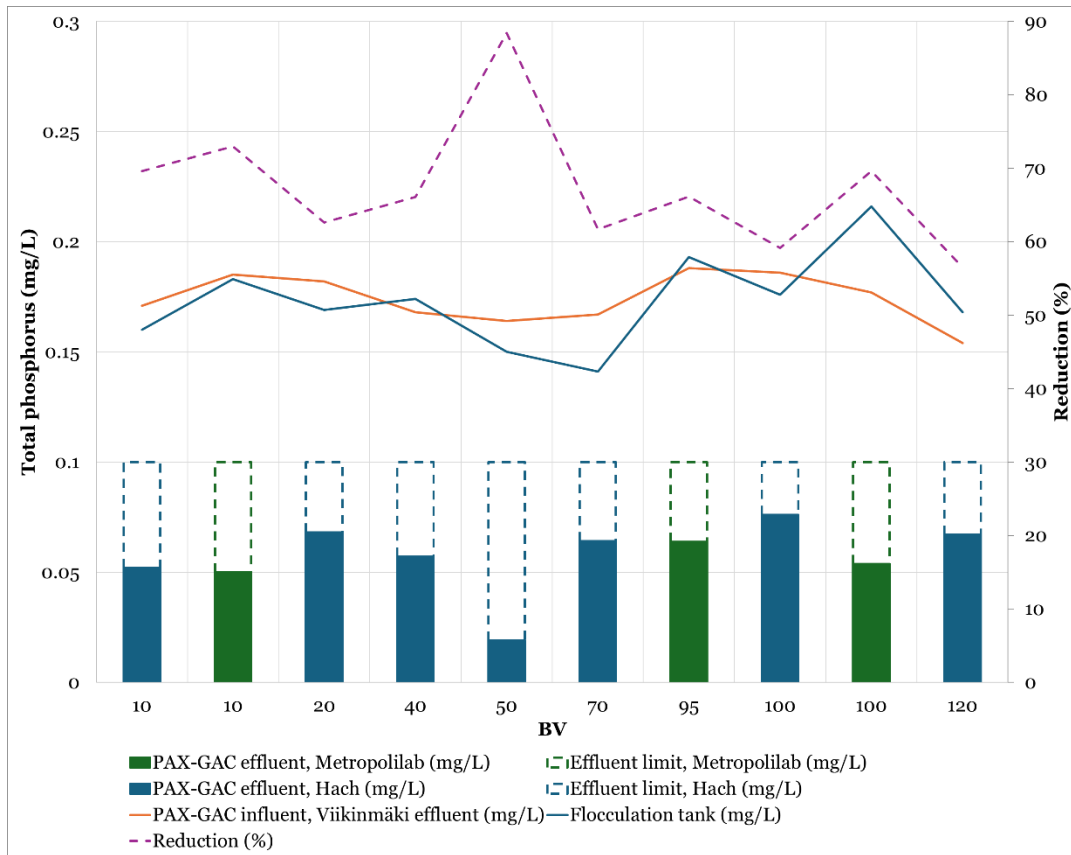


Figure 16. Total phosphorus concentrations and reductions in PAX-GAC filter (with chemical dosing) during the second laboratory measurement campaign.

The two laboratory measurement campaigns are not directly comparable, as both the GAC media was replaced, and the influent concentrations differed between the two campaigns. Both influent and effluent concentrations as well as the calculated reductions of the campaigns are presented in Table 12. During the PAX-GAC campaign, the influent TP and PO₄-P concentrations were slightly higher (0.18 mg/L and 0.09 mg/L on average, respectively) compared with the GAC-only campaign (0.14 mg/L and 0.06 mg/L). Despite the higher influent concentrations, the overall TP reductions remained at a similar level in both the first and the second campaign (65 % and 67 %, respectively). The UV₂₅₄ reduction also remained high (96 %), suggesting that coagulant addition maintained the removal of UV-adsorbing organic compounds.

The PO₄-P reduction was noticeably higher in the first campaign (79 %) than in the second campaign (59 %). The average PO₄-P effluent concentration was also significantly lower during the first GAC-only campaign (0.01 mg/L) than during the second PAX-GAC campaign (0.04 mg/L). However, it should

be noted that most of the $\text{PO}_4\text{-P}$ effluent results were below the analytical measurement range of the cuvette tests (0.05 mg/L), and therefore, no reliable quantitative comparison can be made between the two campaigns. When considering the differences in influent concentrations, further conclusions on the absolute $\text{PO}_4\text{-P}$ removal efficiency cannot be drawn for this campaign. Moreover, only 120 BVs were treated with PAX dosing, and as further observed in the pilot-scale experiments (Section 4.1.4), the PAX-GAC process may require an extended operational period to reach stable operating conditions and fully establish its treatment performance.

The head loss was higher during the PAX-GAC campaign (8.5 cm) compared with the GAC campaign (4.4 cm), which reflects partial filter clogging due to floc accumulation. However, no significant decrease in hydraulic capacity occurred, and the PAX-GAC filter only required two backwashes at approximately 50 and 100 BVs. At 100 BVs, samples of the backwash water were taken both at the start and at the end of the backwashing procedure. The TP concentration in the backwash water decreased from 1.9 mg/L at the beginning to 0.04 mg/L after 20 minutes of backwashing, indicating that TP accumulated in the filter was effectively removed during backwashing. Although only one backwash event was analysed, the results suggest that phosphorus was released with the backwash water (further confirmed in pilot-scale experiments in Section 4.1.4). Moreover, visible flocs were observed in the backwash effluent, indicating efficient mechanical removal of coagulated solids from the GAC bed.

Table 12. Average parameters for the laboratory measurement campaigns. TP concentrations measured at Metropolilab and Viikinmäki laboratory (Hach cuvette tests), PO₄-P, UV₂₅₄ and head loss measured at Viikinmäki.

	First measurement campaign, GAC, average (min – max)	Second measurement campaign, PAX-GAC, average (min – max)
TP, influent (mg/L)	0.14 (0.11–0.21)	0.18 (0.15–0.20)
TP, flocculation tank (mg/L)	-	0.18 (0.14–0.22)
TP, effluent (mg/L)	0.05 (0.03–0.07)	0.06 (0.02–0.08)
TP, reduction (%)	65 (50–77)	67 (57–88)
PO ₄ -P, influent (mg/L)	0.06 (0.04–0.08)	0.09 (0.08–0.12)
PO ₄ -P, flocculation tank (mg/L)	-	0.09 (0.07–0.11)
PO ₄ -P, effluent (mg/L)	0.01 (0.001–0.03)	0.04 (0.02–0.06)
PO ₄ -P, reduction (%)	79 (53–98)	59 (46–73)
UV ₂₅₄ , reduction (%)	99 (98–99)	96 (93–99)
Head loss (cm)	4.4 (3.5–5.0)	8.5 (2.0–20)

4.1.3 Pilot-scale column performance without chemical dosing

The pilot-scale experiments started with an operation period without chemical dosing in both columns to establish baseline conditions for the following measurements with PAX dosing. During this period, both the GAC and PAX-GAC columns demonstrated similar TP removal performance (Figure 17). The pilot influent TP concentration from the Viikinmäki effluent averaged 0.184 mg/L during the operation period without chemical dosing. Both columns achieved effluent TP concentrations below or close to the target limit of 0.1 mg/L, and most samples met this limit, especially at BVs below 195. The GAC effluent TP averaged 0.09 mg/L and the PAX-GAC effluent 0.08 mg/L. This corresponded to TP reductions of 47 % in the GAC column and 52 % in the PAX-GAC column. After approximately 100 BVs, the PAX-GAC column exhibited slightly lower effluent TP concentrations than the GAC column. This difference may be due to phosphorus and TSS

accumulation in the flocculation tank, even though only water was fed (Figure 18 and Figure 19). However, these results confirm that both columns provide comparable phosphorus removal performance under conditions without chemical dosing (Table 13).

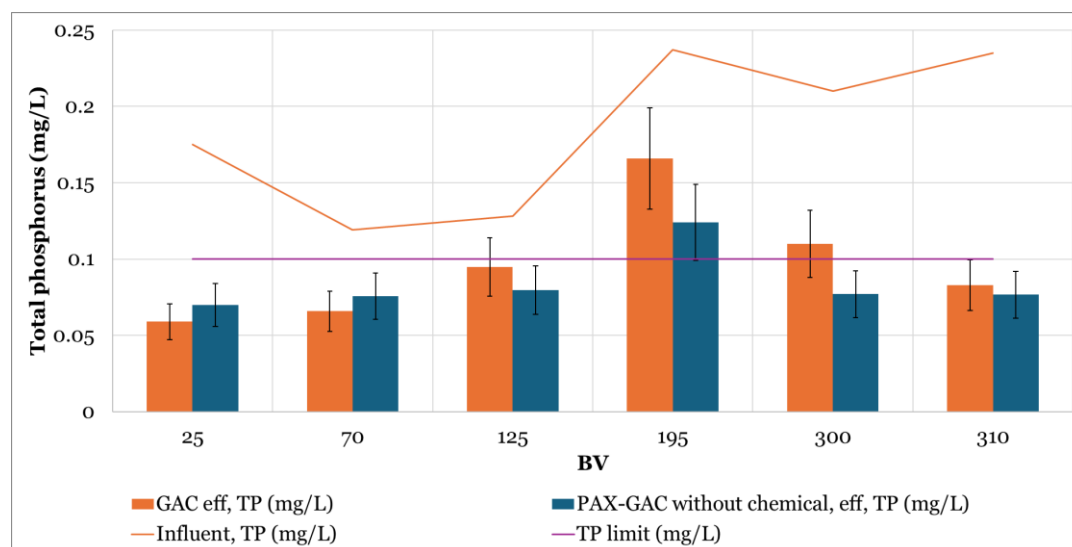


Figure 17. Total phosphorus concentrations in the pilot influent (Viikinmäki effluent) and column effluents (GAC eff and PAX-GAC eff) when both columns were operated without chemical dosing.

The measurement uncertainty for all TP analyses presented in the above and following figures is 20 % and 10 % for TSS, as determined by Metropolilab. All pilot-scale results are reported according to Metropolilab analyses, as the Hach cuvette tests served only as on-site operational control measurements. Table 13 presents all relevant average parameters during the operation phase without chemical dosing along with their respective minimum and maximum values.

Table 13. Average parameters for the pilot-scale operation period without chemical dosing. TP and PO₄-P concentrations measured at Metropolilab, UV₂₅₄ and head loss measured at Viikinmäki.

	GAC, average (min – max)	PAX-GAC, average (min – max)
TP, influent (mg/L)	0.18 (0.12–0.24)	0.18 (0.12–0.24)
TP, flocculation tank (mg/L)	-	0.19 (0.11–0.26)
TP, effluent (mg/L)	0.09 (0.06–0.17)	0.08 (0.07–0.12)
TP, reduction (%)	47 (26–66)	52 (36–67)
PO ₄ -P, influent (mg/L)	0.12 (0.07–0.17)	0.12 (0.07–0.17)
PO ₄ -P, flocculation tank (mg/L)	-	0.11 (0.07–0.14)
PO ₄ -P, effluent (mg/L)	0.07 (0.04–0.10)	0.07 (0.03–0.09)
PO ₄ -P, reduction (%)	31 (-15–67)	34 (-13–74)
UV ₂₅₄ , reduction (%)	84 (68–98)	92 (87–97)
Head loss (cm)	49 (29–150)	44 (18–150)

The slightly lower TP concentrations observed in PAX-GAC column without chemical dosing might be explained by analysing the TP and TSS concentrations in the flocculation tank compared to the pilot influent. Even though the pilot was operated without chemical dosing, the pilot setup required the flocculation tank to remain in place as an intermediate step before the PAX-GAC column.

Figure 19 shows notable accumulation of solids despite the feed without chemical dosing to the flocculation tank. Although the TP concentrations in the flocculation tank were only slightly higher than in the influent (Figure 18), the difference in TSS concentration was much more pronounced. The TSS concentrations in the flocculation tank ranged from 4.0–9.6 mg/L, which significantly exceeds the influent values of 2.0–2.8 mg/L. The measurement range for TSS is 2 mg/L, therefore, the influent values might have been even lower. The accumulation of solids in the flocculation tank occurred even though continuous mixing was maintained throughout the operation without

chemical dosing, indicating that flocs and particulate matter settled and attached to the walls of the plastic IBC tank under moderate mixing conditions. It is important to note that the sampling point was located at the upper water surface of the flocculation tank. Therefore, an additional sampling point in the outlet hose of the flocculation tank would have been useful to determine how much the feed to the PAX-GAC column actually differed from the influent. Although this solid accumulation phenomenon likely contributed to the slightly better filtration performance observed in the PAX-GAC column compared to the GAC column, the two filters can still be considered comparable, as the differences remain moderate and within the 20 % measurement uncertainty.

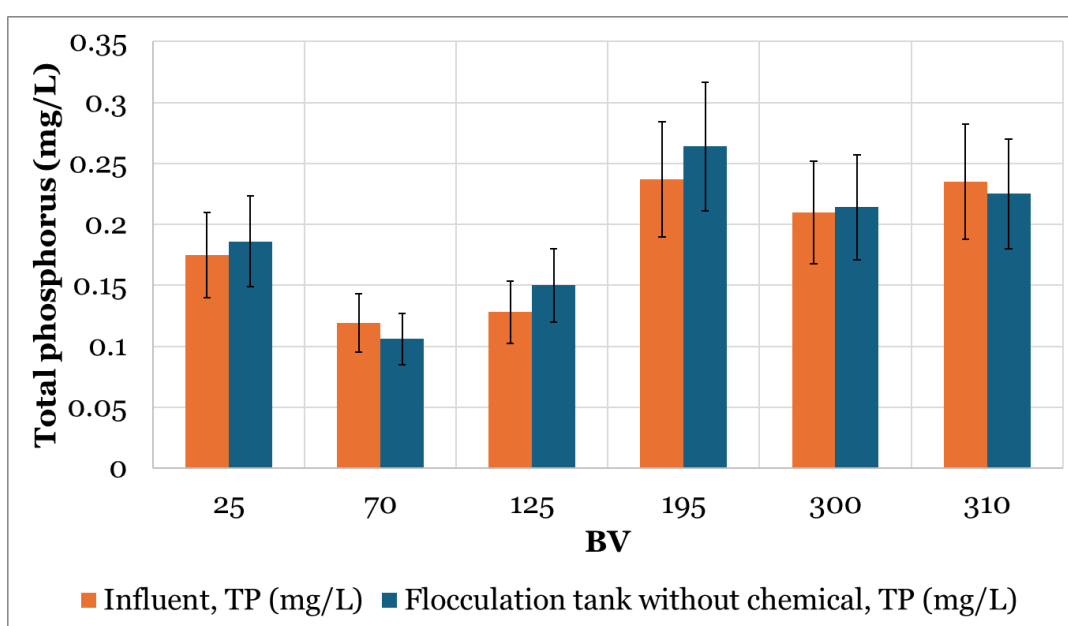


Figure 18. Total phosphorus concentration in the pilot influent (Viikinmäki effluent) and flocculation tank without chemical dosing.

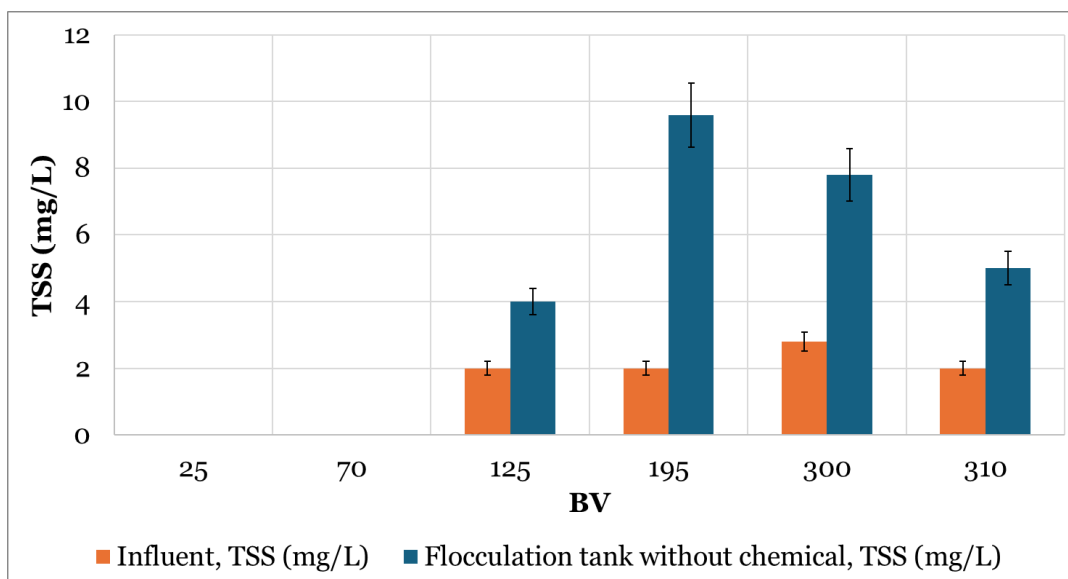


Figure 19. Total suspended solids concentration in the pilot influent (Viikinmäki effluent) and flocculation tank without chemical dosing.

4.1.4 Pilot-scale column performance with PAX dosing

Following the operation period without chemical dosing, PAX dosing was initiated at 330 BVs to the PAX-GAC column at a molar ratio of 20 Al:PO₄-P. The molar ratio of 20 was based on the previous laboratory-scale results and maintained constant throughout the entire chemical dosing period. Although this operation period is referred to as chemical operation phase, the GAC column continued to operate without chemical dosing, serving as a reference line. The results demonstrate improved phosphorus removal in the PAX-GAC column (Figure 20 and Figure 21). After 365 BVs, every effluent TP sample from the PAX-GAC column was lower than the corresponding GAC column sample, with all PAX-GAC concentrations below the 0.1 mg/L TP limit. However, at the start of the chemical dosing period, the PAX-GAC column resulted in slightly higher effluent TP concentrations than the GAC column. This indicates that the PAX-GAC process requires a certain stabilization period before reaching optimal performance. This could be related to the gradual formation of a floc layer on top of the GAC bed. The small and freshly formed flocs generated in the flocculation tank may not be sufficiently dense to be retained by the filter. However, during continued operation, these flocs likely agglomerate with the previously accumulated solids in the upper part of the GAC bed, resulting in the development of a more efficient filtration layer that prevents fine flocs from passing through.

The GAC column also achieved the target TP concentration for most of the samples (except for two samples at 400 and 530 BVs), indicating that effective phosphorus removal can be achieved even without chemical dosing

in the GAC filter. The effluent TP concentration averaged 0.09 mg/L in the GAC column and 0.08 mg/L in the PAX-GAC column. This corresponded to average TP reductions of 38 % and 50 %, respectively. Nevertheless, the test period of 600 BVs was relatively short, and the GAC column is expected to show reduced phosphorus removal due to gradual clogging and loss of solids retention capacity of the filter media. In addition, the advantage of PAX dosing becomes clearer when examining PO₄-P removal (Figure 21). The PAX-GAC column achieved lower PO₄-P concentrations compared to the GAC column, suggesting that PAX dosing specifically enhances the removal of the soluble phosphate fraction. Although the PO₄-P concentration averaged 0.05 mg/L in both columns, the PAX-GAC column achieved higher PO₄-P reduction (34 %) than the GAC column (25 %). This aligns with literature findings that PO₄-P is the most readily targeted phosphorus fraction for chemical phosphorus removal (Benjamin, 2013; Dueñas et al., 2003; Gu, 2014), while particulate phosphorus can be removed through physical filtration alone. Table 14 presents all average values during the chemical operation phase along with their respective minimum and maximum values.

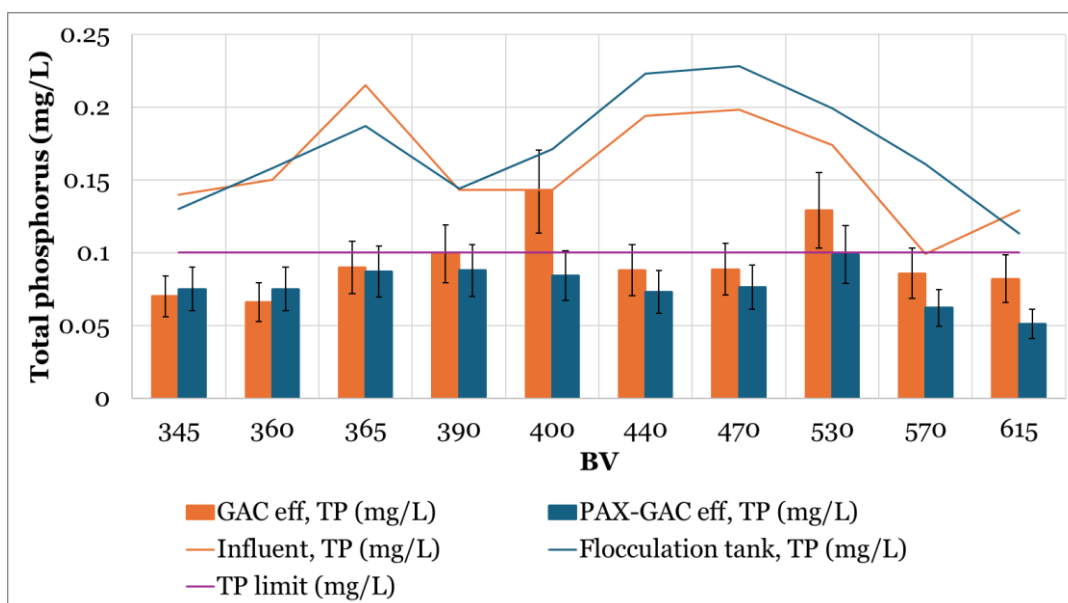


Figure 20. Total phosphorus concentrations in the pilot influent (Viikinmäki effluent), flocculation tank and column effluents (GAC eff and PAX-GAC eff) with chemical operation.

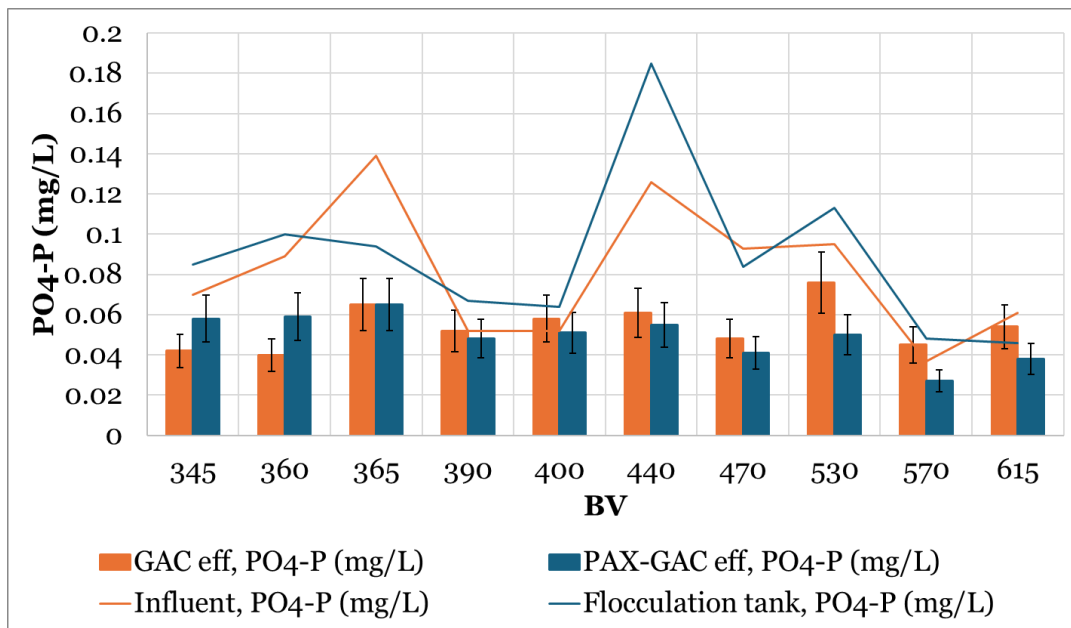


Figure 21. Orthophosphate concentrations in the pilot influent (Viikinmäki effluent), flocculation tank and column effluents (GAC eff and PAX-GAC eff) with chemical operation.

The measurement uncertainty for all TP, TSP and PO₄-P analyses presented in the above and following figures is 20 % and 10 % for TSS, as determined by Metropolilab. All pilot-scale results are reported according to Metropolilab analyses, as the Hach cuvette tests served only as on-site operational control measurements. Table 14 presents all relevant average parameters during the chemical operation phase along with their respective minimum and maximum values.

Table 14. Average parameters for the pilot-scale chemical operation period. TP and PO₄-P concentrations measured at Metropolilab, UV₂₅₄ and head loss measured at Viikinmäki.

	GAC, average (min – max)	PAX-GAC, average (min – max)
TP, influent (mg/L)	0.16 (0.10–0.22)	0.16 (0.10–0.22)
TP, flocculation tank (mg/L)	-	0.17 (0.11–0.23)
TP, effluent (mg/L)	0.09 (0.07–0.14)	0.08 (0.05–0.10)
TP, reduction (%)	38 (0.70–58)	50 (37–62)
PO ₄ -P, influent (mg/L)	0.08 (0.04–0.14)	0.08 (0.04–0.14)
PO ₄ -P, flocculation tank (mg/L)	-	0.09 (0.05–0.19)
PO ₄ -P, effluent (mg/L)	0.05 (0.04–0.08)	0.05 (0.03–0.07)
PO ₄ -P, reduction (%)	25 (-22–55)	34 (1.9–56)
UV ₂₅₄ , reduction (%)	94 (88–99)	92 (83–98)
Head loss (cm)	41 (28–91)	46 (17–120)

Similar to the operation period without chemical dosing, accumulation of TP and TSS was observed in the flocculation tank during PAX dosing (Figure 22 and Figure 23). TP and TSS levels in the flocculation tank exceeded pilot influent values, showing the impact of chemical coagulation and floc formation. Especially the TSS concentration was noticeably higher in the flocculation tank (6.4–18 mg/L) than in the pilot influent (2.0–6.0 mg/L). These accumulated solids in the tank may partially contribute to the lower effluent concentrations observed in the PAX-GAC column. However, the consistently lower PAX-GAC effluent TP concentrations indicate effective coagulation rather than suggesting that improved phosphorus removal would solely be due to flocculation tank accumulation. Additionally, TP and TSS accumulation in the tank can be expected during chemical operation, and as noted in the period without chemical dosing, sampling from the bottom outlet hose of the flocculation tank would provide a more representative picture of the actual feed entering the PAX-GAC column.

Consequently, the noticeably lower TSP concentration in the flocculation tank compared to the pilot influent indicates sufficient chemical coagulation (Figure 24). Low TSP concentrations in the flocculation tank suggests that soluble phosphorus fractions were effectively converted to particulate forms.

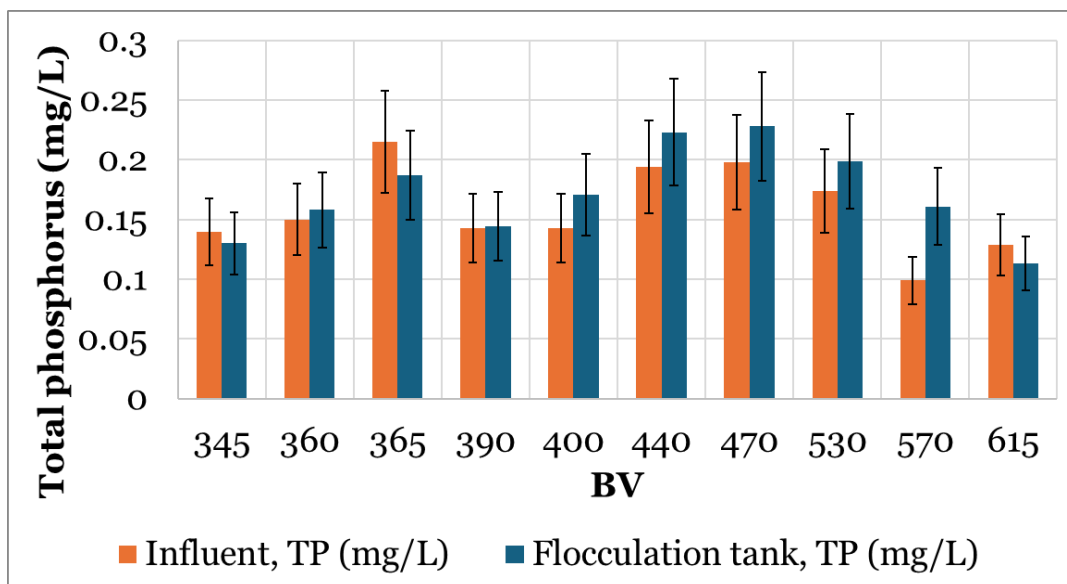


Figure 22. Total phosphorus concentration in the pilot influent (Viikinmäki effluent) and flocculation tank with chemical operation.

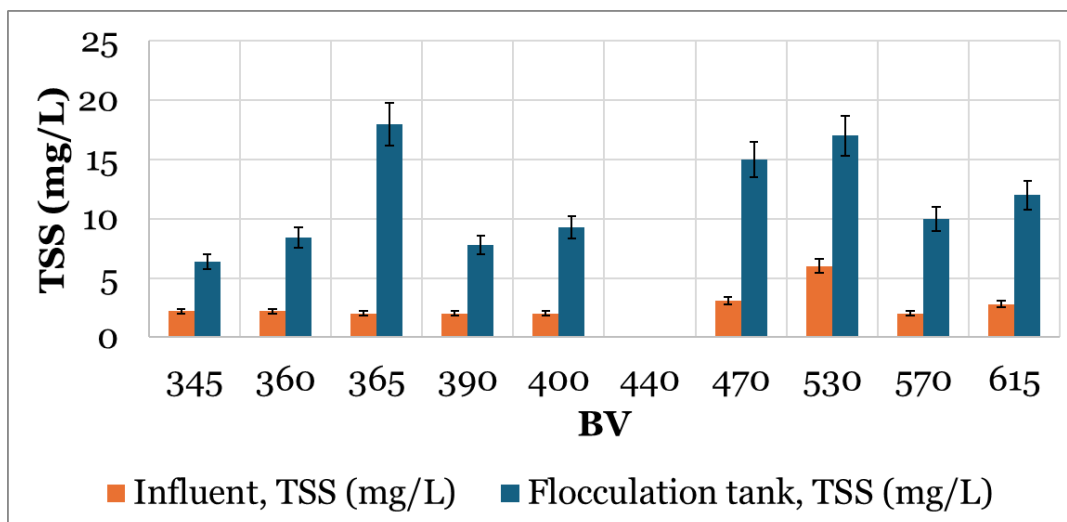


Figure 23. Total suspended solids concentration in the pilot influent (Viikinmäki effluent) and flocculation tank with chemical operation.

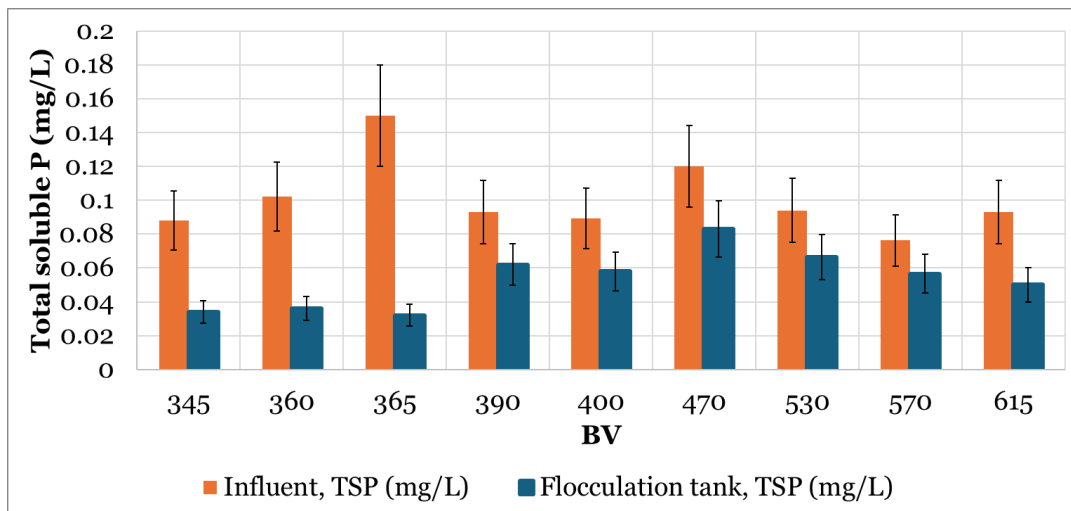


Figure 24. Total soluble phosphorus concentration in the pilot influent (Viikinmäki effluent) and flocculation tank with chemical operation.

The backwash water quality showed clear differences between the GAC and PAX-GAC columns (Figure 25). Samples were collected at the beginning of the water backwash. The PAX-GAC column consistently produced backwash effluent with higher TP concentrations (0.74–3.7 mg/L) than the GAC column (0.29–1.1 mg/L), indicating more effective phosphorus removal in the PAX dosed filter bed. Similarly, TSS concentrations were noticeably higher in the PAX-GAC backwash (64–130 mg/L) compared to the GAC backwash (17–55 mg/L). These findings show that PAX dosing enhanced the GAC filter’s ability to physically capture solids and flocs, allowing greater accumulation of TP and TSS, which were then removed during backwashing. The GAC column without chemical dosing produced backwash effluent with lower concentrations, which shows less efficient removal of TP and TSS during GAC filtration. However, as shown in Figure 23, the TSS load to the PAX-GAC column was higher than that of GAC column, as the solids notably accumulated in the flocculation tank. Therefore, the elevated TP and TSS concentrations in the PAX-GAC backwash effluent are also a result of the higher initial load to the column. Since the PAX-GAC column was designed to function as a mechanical filtration stage for enhanced TP removal, these results indicate that the chemical dosing was successful and achieved its intended function in that regard.

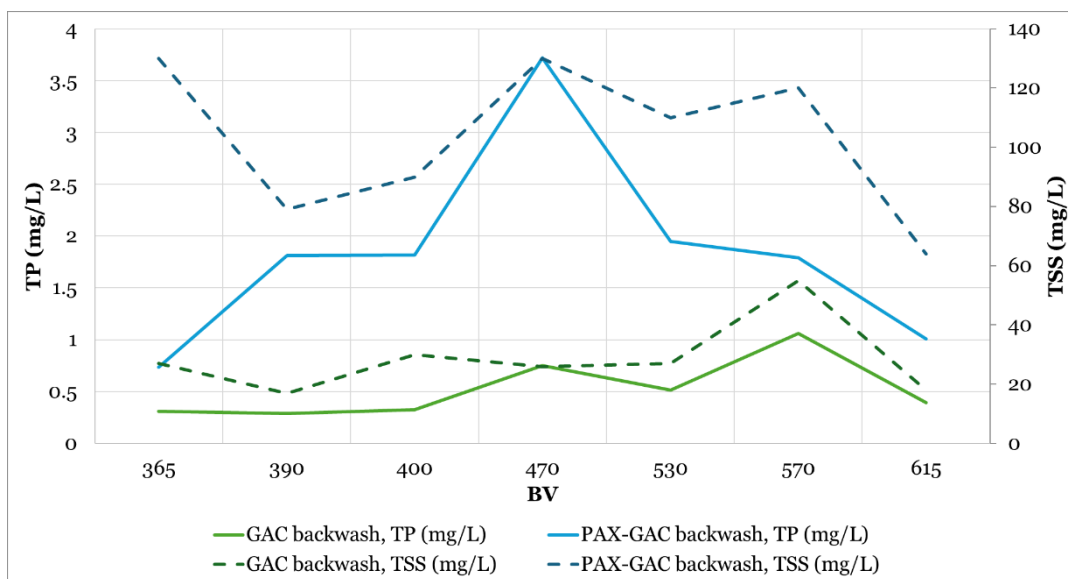


Figure 25. Backwash total phosphorus and total suspended solids concentrations in the GAC and PAX-GAC columns.

4.1.5 Phosphorus fractions

GAC samples were collected from the upper layer of both pilot columns (GAC and PAX-GAC) at the end of the pilot campaign, at approximately 600 BVs. Phosphorus fractionation was conducted on three GAC samples: regenerated GAC from Vanhakaupunki water treatment plant as a baseline GAC (zero BV), spent GAC from the GAC column (600 BV), and spent GAC from the PAX-GAC column (600 BV). Measurements were performed in two rounds at Aalto Water Laboratory: first with single samples following the original protocol with 0.2 g GAC (Figure 6), and second with duplicate samples using doubled sample and reagent amounts (0.4 g GAC with proportionally scaled extractant volumes, e.g., 40 mL of 1 M HCl instead of 20 mL) to ensure sufficient supernatant volume for reliable phosphorus determination. Results presented in Table 15 are based on the second measurement round with duplicate samples and 0.4 g GAC.

Table 15 shows mass balance failure indicating SMT protocol incompatibility with GAC matrix. The sum of inorganic and organic phosphorus did not match measured TP, and metal-bound fractions showed substantial deviations with total inorganic phosphorus. Notably, iron-bound phosphorus was abnormally elevated relative to both inorganic phosphorus and TP, suggesting non-selective extraction or matrix interference. These mass balance failures far exceed acceptable analytical uncertainty, indicating fundamental incompatibility between the fractionation protocol and GAC matrix.

The SMT protocol was originally developed for sediments and sewage sludge (Gonzalez Medeiros et al., 2005). The porous structure of GAC and strong adsorption properties create fundamentally different extraction conditions. In terms of characteristics presented in Table 15, iron-bound phosphorus fractions were elevated in both GAC and PAX-GAC column samples, suggesting retention of iron-bound flocs from Viikinmäki WWTP's process. However, due to unreliable mass balance, quantitative interpretation is not possible and detailed discussion of phosphorus fractions is excluded. This highlights that sequential extraction methods require fundamental validation for activated carbon matrices.

Table 15. Phosphorus fractionation results from GAC samples (average values from duplicate measurements) showing mass balance failure indicating SMT protocol incompatibility with GAC matrix.

Sample	Al-P (µg/L)	Fe-P (µg/L)	Inorg-P (µg/L)	Org-P (µg/L)	TP (µg/L)
Baseline GAC (zero BV)	8.5	107	11.3	9.0	9.0
GAC (600 BV)	8.5	3325	57.2	10.8	9.6
PAX- GAC (600 BV)	8.7	2124	21.9	9.1	10.3

Al-P = aluminium-bound phosphorus, Fe-P = iron-bound phosphorus, Inorg-P = inorganic phosphorus, Org-P = organic phosphorus, TP = total phosphorus.

In addition to the GAC media samples, water samples were collected from the upper water layer of both pilot columns at the end of the pilot campaign, at approximately 600 BVs. Samples were taken in duplicates from an initial 10 L grab sample and analysed at Metropolilab. Samples were analysed for TP, TSP and PO₄-P, which represent the same analyses routinely monitored throughout the study (Section 3.2), rather than a formal fractionation protocol, but sampled from the upper filter layer instead of the usual effluent sampling point at the bottom of the column. The results are presented as phosphorus fractions calculated from these measurements as arithmetic means from the duplicate samples. Total particulate phosphorus was calculated by subtracting TSP from TP. TSP was further divided into soluble reactive phosphorus, approximated as PO₄-P, and soluble non-reactive phosphorus, calculated by subtracting PO₄-P from TSP. Further water-phase fractionation was not conducted at Aalto Water Laboratory due to the low phosphorus concentrations.

The upper layer of the PAX-GAC column showed significantly higher particulate fraction (1.7 mg/L) compared to the GAC column (0.17 mg/L), while soluble fractions (soluble reactive and non-reactive phosphorus) remained lower in the PAX-GAC column (Figure 26). This demonstrates successful floc formation in the PAX-GAC filter, where the formed flocs are retained in the upper layer of the PAX-GAC bed. The dominance of particulate fractions in the PAX-GAC column shows that PAX dosing effectively converted soluble fractions into filterable flocs that accumulate in the upper layer of the filter. This is further confirmed by the soluble reactive fraction, approximated as $\text{PO}_4\text{-P}$, which was lower in the PAX-GAC column (0.03 mg/L) than in the GAC column (0.07 mg/L). The TSP was also lower in the PAX-GAC column (0.05 mg/L) than in the GAC column (0.08 mg/L). However, the soluble non-reactive fraction was higher in the PAX-GAC column (0.02 mg/L) than in the GAC column (0.007 mg/L).

The lower TSP concentration in the PAX-GAC column upper layer confirms successful chemical coagulation, as soluble reactive fraction is effectively removed through the formation of aluminium-phosphate-hydroxo complexes. However, the elevated soluble non-reactive phosphorus fraction in the PAX-GAC column indicates the presence of refractory phosphorus species in Viikinmäki effluent that resist removal through chemical coagulation. As discussed in Section 2.3.1, soluble non-reactive fraction comprises primarily organic phosphorus compounds, which do not react with traditional metal salt coagulants and exhibits significantly lower removal efficiency than phosphates or inorganic phosphorus (Gu, 2014; Li and Brett, 2015; Neethling et al., 2007). Although the soluble reactive fraction was approximated as $\text{PO}_4\text{-P}$ in this calculation, the same hypothesis remains, as $\text{PO}_4\text{-P}$ is the most readily targeted phosphorus fraction for chemical phosphorus removal (Benjamin, 2013; Dueñas et al., 2003; Gu, 2014). These findings and the dominance of particulate fractions in the PAC-GAC column validates the mechanical filtration approach that was the fundamental of this study.

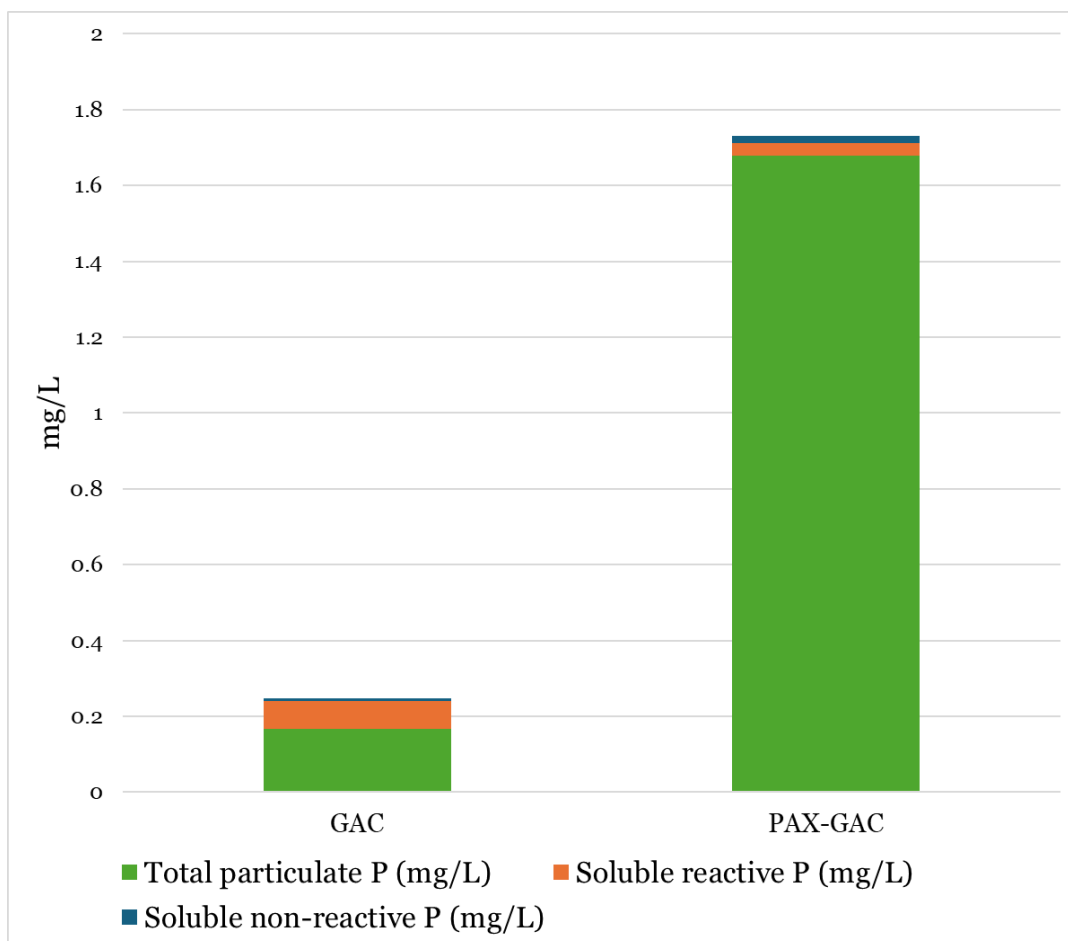


Figure 26. Phosphorus fractions in the upper water layer of both pilot columns at the end of pilot campaign (600 BVs). Phosphorus fractions were calculated from MetropoliLab measurements as arithmetic means from duplicate samples. Further water-phase fractionation was not conducted.

4.1.6 Effect of coagulation on hydraulic performance

Head loss development in GAC and PAX-GAC columns remained manageable throughout pilot-scale operation, both with and without chemical dosing (Figure 27). The PAX-GAC column with PAX dosing (purple dashed line) showed occasional head loss peaks but no significant filter clogging, with an average head loss of approximately 46 cm compared to 41 cm in the GAC column (orange line) during the chemical operation period. Backwash intervals of 1–2 days were maintained for both columns, and this backwash regime was already required during the initial operation phase without chemical dosing (blue dashed line, before 330 BVs). During the operation phase without chemical dosing, longer backwash intervals (3 days) were tested, but resulted in excessive head loss, which is shown in overflow events (150 cm head loss) during the operation period without chemical. It

should be noted that the pilot was only operated during working hours, and this non-continuous operation allowed the GAC media and accumulated solids to settle between operation. This affects the comparability of backwash intervals to literature values. In literature, usual backwash intervals are between 24 hours in wastewater treatment applications (Boller and Kavanaugh, 1995; Crittenden et al., 2012), but in this pilot study, the actual operational runtime between backwashes was only 7–12 hours. Due to the additional mechanical stress from GAC bed settling during standstill periods, these intervals are not significantly shorter than those reported in continuously operated columns in literature. However, these backwash intervals cannot be directly compared to continuous full-scale operation. Additionally, as discussed in Section 3.4.2, the GAC column operated at a slightly higher flow rate (250 L/h) than the PAX-GAC column (230 L/h) during the chemical operation phase due to pressure-reducing valve failure at 280 BVs, which affected the influent pump of the GAC column. This may have contributed to marginally different hydraulic conditions between the columns. Higher flow rate also resulted in the GAC column operating approximately 20 BVs more than the PAX-GAC column over the pilot-scale campaign. However, results in this thesis are presented at equivalent BVs for clarity, as calculated BVs are inherently theoretical estimates.

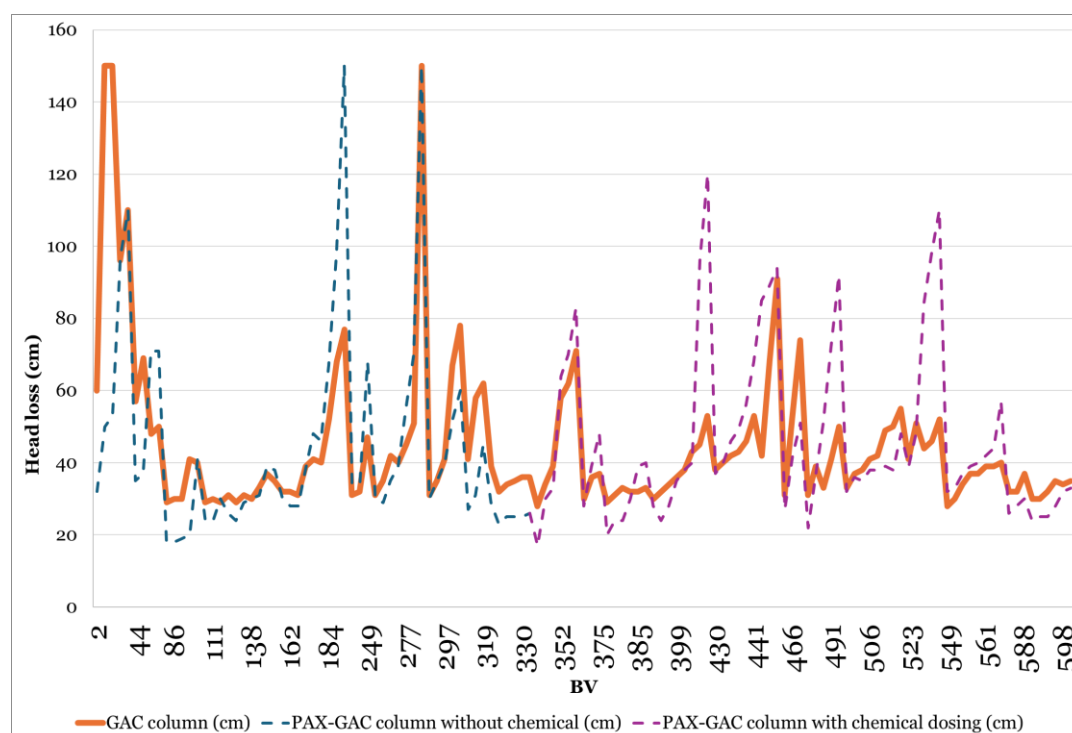


Figure 27. Head loss development during the pilot-scale campaign in GAC and PAX-GAC columns.

4.1.7 Residual aluminium and SEM-EDS analysis of GAC

Residual aluminium concentrations in the PAX-GAC column effluent remained low throughout the pilot operation (Figure 28). Total aluminium in the PAX-GAC effluent ranged from 0.03 to 0.32 mg/L, with dissolved aluminium consistently below 0.2 mg/L, indicating minimal release of coagulant into the effluent. In addition, backwash water showed high total aluminium concentrations (5–28 mg/L) with relatively low dissolved aluminium concentrations (0.3–6 mg/L). This confirms that aluminium is effectively removed from the GAC filter during backwashing. The predominance of particulate aluminium in both effluent and backwash water demonstrates efficient coagulation and that the formed flocs are sufficiently retained and removed by the physical GAC filtration stage.

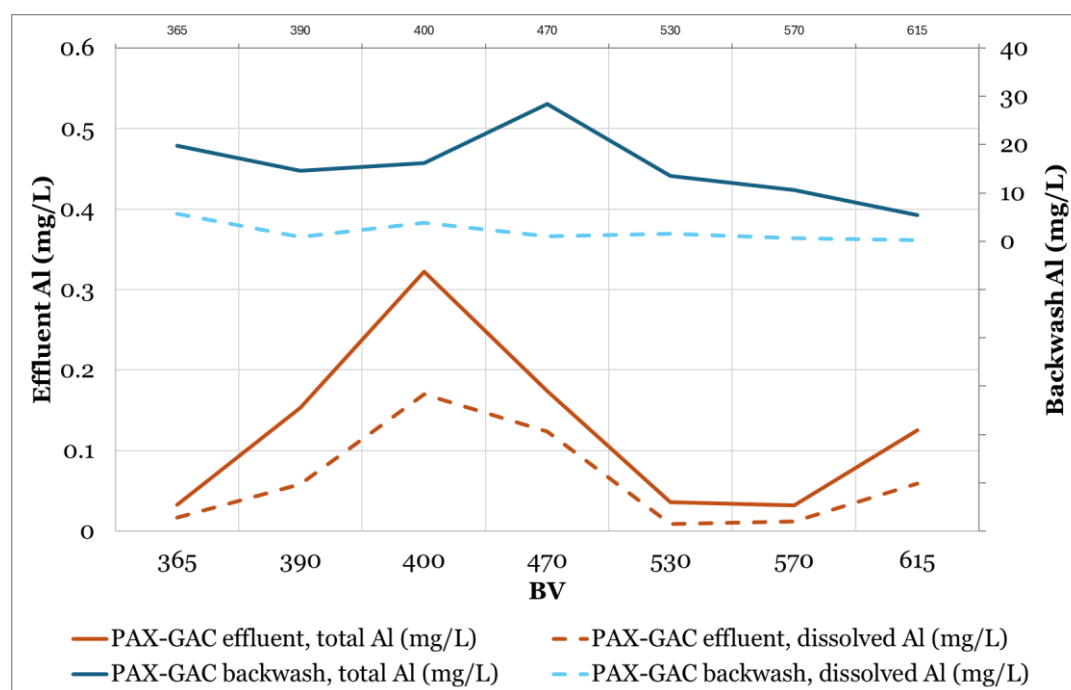


Figure 28. Aluminium concentrations in the PAX-GAC effluent and backwash effluent.

At the end of the pilot campaign, GAC samples from upper layer of both pilot columns were taken and analysed at Aalto Laboratory for SEM imaging and EDS analysis. Regenerated GAC from Vanhakaupunki water treatment plant was also analysed as a baseline GAC. SEM micrographs reveal surface modification of GAC media during pilot-scale operation (Figure 29). Baseline GAC shows well-defined porous structure with clean surfaces (Figure 29A). After 600 BVs of operation without chemical dosing, the GAC filter media shows partial coverage with biofilm and organic residues, although the underlying pore structure remains visible (Figure 29B). In contrast, the PAX-

GAC column demonstrates substantial surface coating that conceals the pore structure and blocks pore openings (Figure 29C). This visualization confirms that PAX dosing does alter GAC surface characteristics through formation of aluminium-phosphate precipitates, which may impact both adsorption capacity and hydraulic performance. However, high aluminium concentrations in backwash effluent, as shown in Figure 28, indicate efficient physical removal of aluminium-phosphate flocs during backwashing, preventing excessive buildup and maintaining filtration performance.

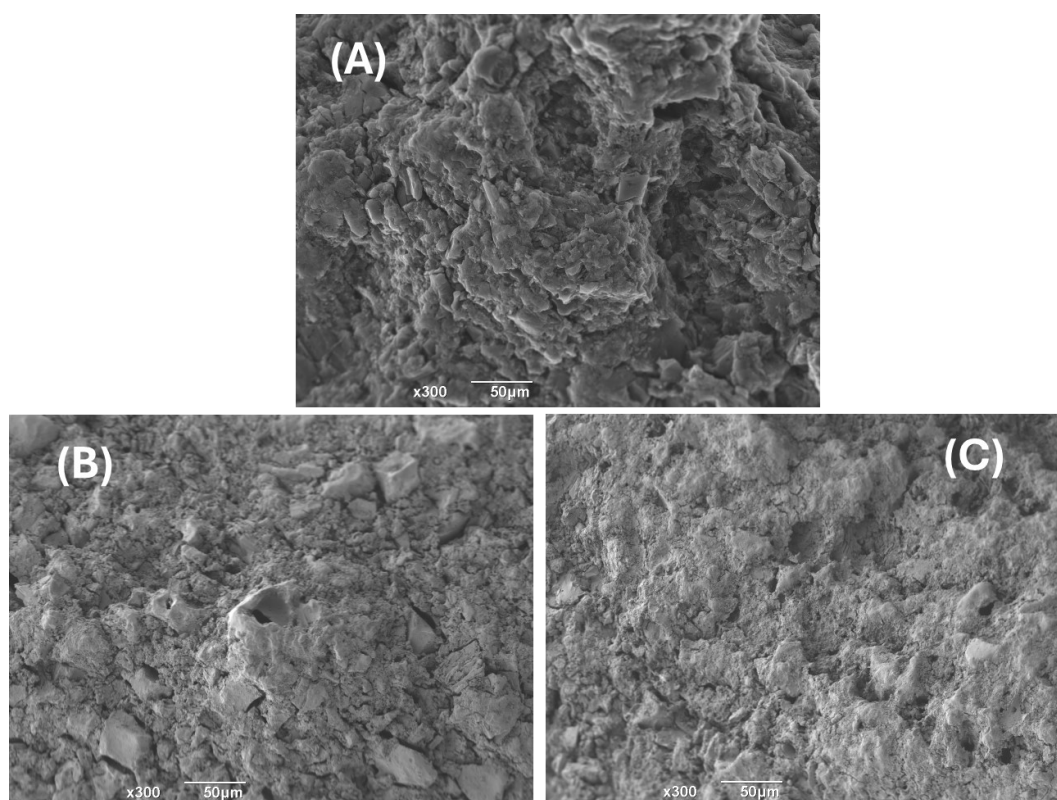


Figure 29. SEM micrographs of GAC surfaces at 300x magnification. (A) Baseline regenerated GAC (zero BV), (B) GAC after 600 BV operation without chemical dosing, (C) PAX-GAC after 600 BV operation, of which 270 BVs with chemical dosing. Scale bars = 50 μm .

EDS analysis of the GAC media confirms accumulation of coagulant-derived elements on GAC surface during combined treatment. The aluminium content increased from 1.23 wt% (baseline GAC) to 2.65 wt% in PAX-GAC. Iron showed pronounced accumulation in both GAC column (3.31 wt %) and PAX-GAC column (5.49 wt%) compared to the baseline GAC (1.82 wt%). This likely reflects to FeSO_4 used as a precipitant in Viikinmäki WWTP process, as indicated by the increased sulfur percentage. Additionally, phosphorus was absent in baseline GAC but reached 0.17 wt% in GAC sample and 0.37 wt% in PAX-GAC sample, demonstrating phosphorus retention on the carbon surfaces in both pilot columns. Similarly, the decrease in carbon

content and increase in oxygen content in both pilot columns indicates surface coating with metal hydroxides and phosphate precipitates. These findings suggest that metal-phosphate complexes form and accumulate on GAC surfaces to some extent, especially during PAX dosing. However, the observed changes after 600 BVs of operation remain relatively moderate, and long-term accumulation patterns cannot be predicted from these short-term results.

Table 16. Elemental composition (weight %, wt%) of GAC samples determined by EDS analysis. Baseline regenerated GAC and GAC samples from the upper layer of both pilot columns after 600 BVs of operation were analysed.

Element	Baseline GAC (zero BV), wt%	GAC (600 BV), wt%	PAX-GAC (600 BV), wt%
Al, aluminium	1.23	1.73	2.65
Au, gold	5.18	6.92	5.24
C, carbon	78.81	67.62	60.61
Ca, calcium	2.19	0.77	1.25
Cl, chlorine	0.09	-	-
Fe, iron	1.82	3.31	5.49
Mg, magnesium	0.10	0.11	0.18
Mn, manganese	1.10	0.46	0.87
O, oxygen	4.97	11.61	17.96
P, phosphorus	-	0.17	0.37
Pd, palladium	2.86	4.02	2.95
S, sulfur	0.64	1.45	1.05
Si, silicon	1.00	1.83	1.37

4.2 Micropollutant removal

Micropollutant removal was monitored during the chemical operation period of the pilot-scale experiments to evaluate whether chemical coagulation affects GAC adsorption capacity. This section presents the removal efficiencies for EU Directive indicator substances in both GAC and PAX-GAC columns (Section 4.2.1), followed by analysis of UV₂₅₄ as a surrogate parameter for micropollutant removal (Section 4.2.2).

4.2.1 Pilot-scale column performance

Micropollutant removal efficiency remained high in both GAC and PAX-GAC column during the chemical operation period (Table 17). Table 17 presents average concentrations for indicator substances from five sampling events for the Viikinmäki influent and the effluents of both pilot columns, along with the corresponding average removal efficiency percentages. Almost all of the

micropollutant concentrations in the pilot effluents were below the LOQ, therefore, the removal percentages were calculated using half of LOQ values, as suggested in literature (Sauter et al., 2021). When influent concentrations were also below LOQ, removal efficiency could not be determined. Average removal efficiencies ranged from 95 % to 99 % for all measured compounds in both columns. Chemical dosing in the PAX-GAC column did not significantly affect micropollutant removal efficiency compared to the GAC column. However, the results do not provide an indication of long-term performance, as the pilot operation period was only about 600 BVs.

Micropollutants were analysed at Eurofins and total of six sampling events were conducted during the chemical operation period between 7 August and 1 October (320–600 BVs of operation). However, the removal efficiencies are calculated for only five sampling events (between 7 August and 25 September), as Viikinmäki influent concentration was not measured in the last sampling event (1 October). In the last sampling event, a sample from the flocculation tank was taken alongside the Viikinmäki effluent sample, to verify whether any changes in micropollutant concentrations occurred in the tank, e.g., due to potential sorption to the plastic container. No such changes were observed, and the concentrations in the flocculation tank were of the same magnitude as in the Viikinmäki effluent. Therefore the feed to both GAC and PAX-GAC columns can be considered comparable. Additionally, in the last sampling event, the indicator substance concentrations remained near or below the LOQ in both columns, similarly to previous sampling events. Therefore, the average concentrations for GAC and PAX-GAC effluents are presented for all six sampling events, but as can be seen from Table 17, almost all of the concentrations were below LOQ.

Removal efficiencies are reported relative to the Viikinmäki influent, in accordance with the EU Directive's 80 % removal requirement, which is defined with respect to the influent wastewater. Viikinmäki effluent concentrations were also measured, but as shown in Table 5, the effluent concentrations occasionally exceeded the influent concentrations. Therefore, the removal efficiencies were not calculated relative to the Viikinmäki effluent, which could result in overestimated removal efficiencies for the GAC and PAX-GAC columns. Removal efficiencies are therefore presented solely relative to the Viikinmäki influent concentrations, following the EU Directive's guidance.

Table 17. Concentrations of EU Directive 2024/3019 indicator substances and removal efficiencies in GAC and PAX-GAC columns. Six sampling events were conducted during the chemical operation period (320–600 BVs).

Indicator substance	Viikinmäki influent, µg/L	GAC effluent, µg/L	PAX-GAC effluent, µg/L	GAC removal efficiency	PAX-GAC removal efficiency
Category 1 (substances that can be very easily treated)					
Amisulpride	0.11	<0.01	<0.01	95 %	95 %
Carbamazepine	0.12	<0.005	<0.005	97 %	98 %
Citalopram (+Escitalopram)	0.20	<0.010	<0.010	97 %	97 %
Clarithromycin	<0.10	<0.01	<0.01	-	-
Diclofenac	0.79	0.013	0.013	98 %	98 %
Hydrochlorothiazide	0.57	<0.050	<0.050	96 %	96 %
Metoprolol	0.17	<0.005	<0.005	99 %	99 %
Venlafaxine	0.58	<0.005	0.006	99 %	99 %
Category 2 (substances that can be easily disposed of)					
Benzotriazole	2.4	<0.04	<0.04	99 %	99 %
Candesartan	0.92	<0.05	<0.05	97 %	97 %
Irbesartan	<0.10	<0.01	<0.01	-	-
4- and 5-Methylbenzotriazole	0.73	<0.01	<0.01	99 %	99 %

4.2.2 UV₂₅₄ as a surrogate parameter for micropollutant removal

Micropollutant removal showed consistently high efficiency in relation to UV₂₅₄ reduction in both pilot columns (Figure 30 and Figure 31). Reduction of both micropollutants and UV₂₅₄ exceeded 90 % relative to the Viikinmäki WWTP influent, with no significant difference observed between the GAC and PAX-GAC columns. Therefore, the data suggests that a strong reduction in UV₂₅₄ is associated with efficient micropollutant removal. However, reliable correlation analysis between UV₂₅₄ and micropollutant reduction could not be performed, as removal efficiencies above 95 % do not yield reliable correlation coefficients (Anumol et al., 2015). This limitation is present in UV₂₅₄ reduction and micropollutant removal studies where high removal rates compress the data distribution (Anumol et al., 2015).

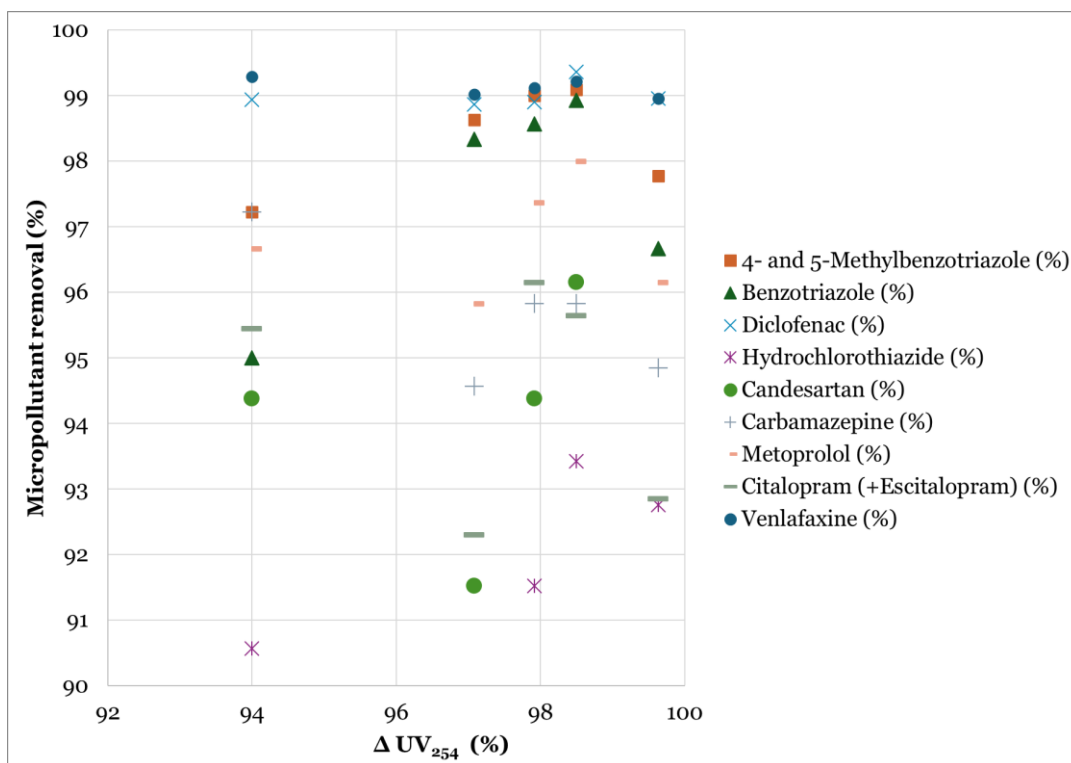


Figure 30. Removal of indicator micropollutants with corresponding UV₂₅₄ reductions in the GAC column.

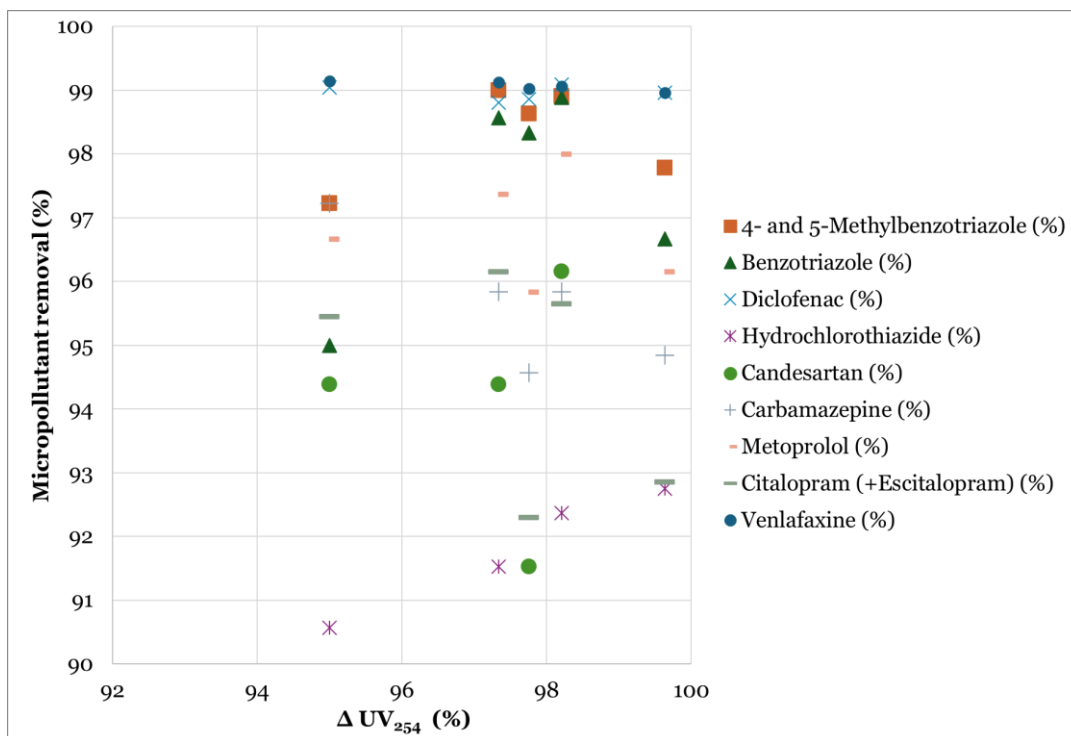


Figure 31. Removal of indicator micropollutants with corresponding UV₂₅₄ reductions in the PAX-GAC column.

Although direct correlation between UV_{254} and micropollutant removal efficiency could not be established due to high removal rates, both pilot columns showed consistent UV_{254} trends throughout the chemical dosing phase (Figure 32). The UV_{254} absorbance of the pilot influent (Viikinmäki effluent) remained at a similar level throughout the entire pilot-scale campaign, averaging on 0.29 (min–max: 0.22–0.47). The resulting average UV_{254} reductions were 94 % in the GAC column and 92 % in the PAX-GAC column, relative to the pilot influent. An increasing trend in UV_{254} absorbance is evident in both GAC and PAX-GAC effluents, as well as decreasing trend in UV_{254} reduction (Figure 32), with the exception of the measurement at 515 BV, which may represent analytical variability or sampling error. The continuous upward trend in effluent UV_{254} absorbance suggests that UV_{254} has not reached saturation, indicating accumulation of UV-absorbing compounds in the effluent. However, given the established correlation between UV_{254} reduction and micropollutant removal (Altmann et al., 2016a; Wittmer et al., 2015), the gradual increase in UV_{254} absorbance in the effluents suggests that micropollutant removal efficiency would decline with extended operation. Nevertheless, quantitative analysis of breakthrough behaviour for individual micropollutants was not possible in this study due to the limited operational period of approximately 600 BVs.

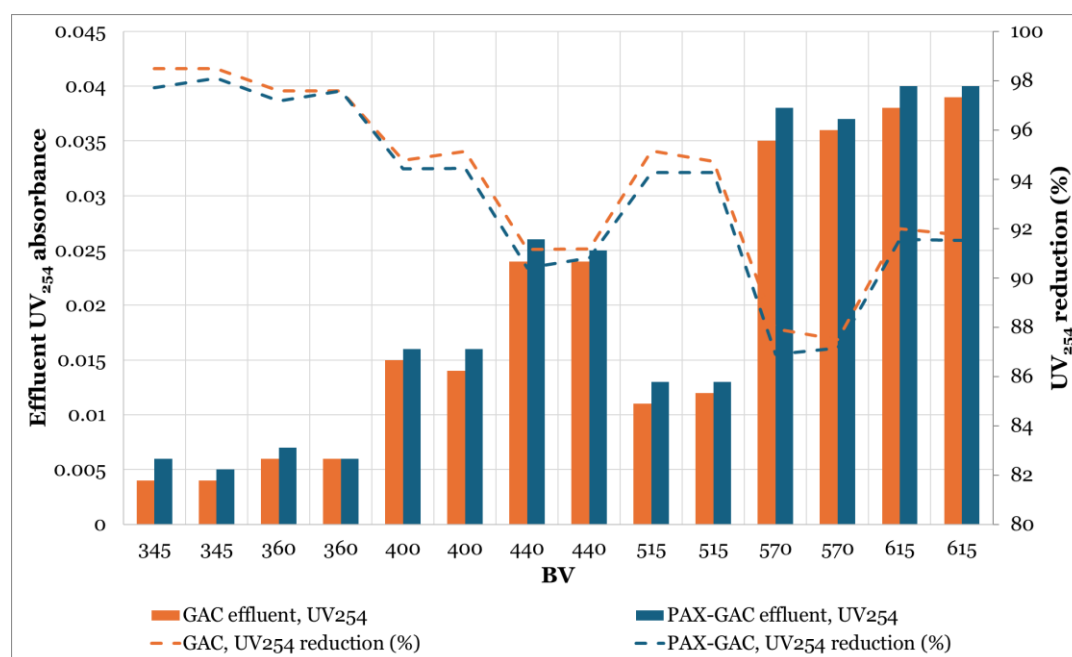


Figure 32. Pilot column effluent UV_{254} absorbances with corresponding UV_{254} reductions during the chemical operation phase.

5 Discussion

This chapter discusses the experimental findings of this study in relation to previous studies and identifies the key factors affecting process performance and result interpretation. The discussion first compares the results of this study with recent European pilot-scale studies (Section 5.1), followed by discussion of technical limitations and experimental constraints that affected process optimization (Section 5.2). Analytical uncertainties and their impact on result interpretation are addressed in Section 5.3. Finally, implementation considerations for full-scale application and recommendations for future research are presented in Section 5.4.

5.1 Comparison of the results with previous studies

The integrated coagulation and GAC filtration process performance in this study aligns with recent European research, although there are notable differences in the initial WWTP effluent TP concentrations. Previous European pilot studies achieved TP concentrations of around 0.1–0.15 mg/L, using molar ratios of 4–5 mol coagulant/reactive phosphorus with initial WWTP effluent concentrations of 0.2–0.6 mg/L TP (Altmann et al., 2016b; Locher and Blind, 2024; Sauter et al., 2021; STOWA, 2023). The present study operated under significantly lower effluent concentrations, with Viikinmäki effluent TP concentrations averaging below 0.2 mg/L. This required a higher coagulant dose of 20 mol Al:PO₄-P to achieve the 0.1 mg/L target, which highlights the challenge of achieving efficient removal at ultra-low TP concentrations, where the stoichiometric relationships no longer follow those of standard phosphorus removal applications.

Micropollutant removal efficiency was over 90 % for almost all of the indicator substances in both the GAC and PAX-GAC column, thus, exceeding the removal requirement of 80 % set by the EU directive. As the pilot-scale campaign only lasted for approximately 600 BVs, these results are not comparable to long-term operation. However, in combined coagulation and GAC filtration studies, the addition of coagulant has not been demonstrated to significantly decrease micropollutant removal efficiency. Altmann et al. (2016b) reported over 80 % removal for well-adsorbing compounds up to 10 000 BVs, while Locher and Blind (2024) achieved 73–76 % average removal for seven monitored micropollutants over 32 000 BVs. The results of this study indicate that with fresh GAC, coagulation does not lead to any significant differences in micropollutant removal performance. On the other hand, this result is also further supported by the fact that phosphorus and micropollutant removal occur through two different, coexisting mechanisms, as micropollutants adsorb directly onto the GAC surface and phosphorus

removal depends primarily on chemical coagulation followed by physical filtration. This allows both processes to operate in parallel, assuming that the accumulated floc layer does not create excessive hydraulic resistance or reduce the contact time for micropollutant adsorption.

Although the GAC saturation and breakthrough behaviour could not be assessed in this study, it could potentially be assumed that if coagulation enhances the removal of not only TP and TSS but also dissolved substances, the adsorption capacity and service life of the GAC media could even be extended. This would require that instead of solely relying on adsorption, part of the compounds that would otherwise adsorb onto the GAC surface were to be removed during backwashing. However, SEM and EDS analyses indicated surface accumulation of metal-phosphate precipitates on the GAC surface, which may conversely reduce long-term adsorption capacity through pore blockage and diminished surface area, while potentially increasing hydraulic resistance over extended operation. Nevertheless, this remains as a highly theoretical consideration, as the pilot-scale campaign was limited to three months. Therefore, the results do not reflect the long-term impact of coagulant dosing on hydraulic performance, GAC saturation or the decrease in micropollutant removal efficiency.

The evaluation of UV_{254} as a surrogate parameter in this study highlighted the limitations presented in recent studies. According to Anumol et al. (2015), only samples with removals between 5 % and 95 % should be chosen for correlation models, as high removal rates might lead to clustering of data points and bias the R^2 and other correlation values. As the present study encountered this limitation with both UV_{254} and micropollutant removal exceeding 95 % for most samples, quantitative correlation analysis was not feasible. However, there was a consistent observation that high UV_{254} reduction (>90 %) correlated with high micropollutant removal efficiency. This finding supports the assumption that UV_{254} could be used as an operational indicator for micropollutant removal, as many studies have reported strong correlations for UV_{254} as a surrogate parameter (Altmann et al., 2016a; Wittmer et al., 2015).

Hydraulic performance and backwash regimes in this study showed both similarities and differences compared to literature. Backwashing frequency and clogging of the filter bed was initially identified as one of the main concerns in the combined process, as reported in many literature studies (Telgmann et al., 2020; Zettl, 2023). As typical wastewater treatment applications target approximately 24 hours long backwash cycles, the combined coagulation and GAC process has been reported to require backwashing up to four times per 24 hours (Telgmann et al., 2020). In the present study, the pilot maintained 1–2 day backwash intervals for both

columns, both with and without chemical dosing. Therefore, no significant differences were observed between the GAC and PAX-GAC columns, as this backwashing frequency was already required during the operation without chemical dosing for both columns. This may also be attributed to the filter nozzles of the pilot, the type of GAC used, pilot influent composition, or other factors. Nevertheless, excessive clogging of the filter was not observed in the PAX-GAC column as a result of coagulation. However, these results do not directly allow for comparison between long-term operation or full-scale implementation.

5.2 Technical limitations and experimental constraints

Many process design and operational constraints limited the optimization of the combined coagulation and GAC filtration process. Primarily, the pilot flocculation tank configuration was constrained by the use of an existing mixer from Viikinmäki WWTP, originally designed for 1 m³ tank volumes. Although the mixer blades were shortened to reduce mixing intensity, the mixer required a flocculation volume of approximately 125 L, corresponding to a 30-minute HRT. This is up to three times longer than typical literature values of 6–8 minutes (STOWA, 2023; Telgmann et al., 2020). Therefore, the optimization of HRT and mixing intensity was not possible in the pilot-scale study. Laboratory-scale experiments were also conducted without optimizing the mixing regime, as conditions were maintained as similar to the pilot configuration as possible, to ensure comparability between the two scales. Additionally, low flow velocities in the pilot configuration prevented implementation of a separate rapid mixing stage, which is usually reported essential for effective coagulant dispersion and further floc formation (Benjamin, 2013). Therefore, both the laboratory- and pilot-scale configurations consisted only of a 30-minute slow mixing phase. The absence of rapid mixing phase might require higher coagulant doses than optimal mixing conditions.

Although the backwash regime and hydraulic performance was similar at both pilot columns during the operation periods with and without chemical dosing, it should be noted that during the chemical operation period, the GAC column received a slightly higher flow rate (250 L/h) compared to the PAX-GAC column (230 L/h), which may have influenced hydraulic performance to some extent. This difference was due to a pressure-reducing valve failure at around 280 BVs, after which the flow rate of GAC column remained at 250 L/h until the end of the pilot campaign. Consequently, the GAC column achieved approximately 20 BVs more than the PAX-GAC column over the monitoring campaign. However, results in this thesis are presented at equivalent BV values for both pilot columns, as calculated BVs are inherently theoretical estimates based on flow rates.

The pilot was also operated intermittently due to reliability concerns without automated control. This allowed GAC media to settle between operation and complicated comparison with continuous operation literature values. Therefore, the backwash regime was determined based on initial observations and sampling frequency rather than systematic optimization. Additionally, the lack of PO₄-P monitoring and automated PAX dosing required manual dosing, which likely resulted in dose variability relative to actual pilot influent concentrations. Furthermore, technical issues with the Viikinmäki effluent Phosphax analyzer during flocculation jar tests resulted in differences between the nominal and actual molar ratios. Although these limitations did not necessarily affect the experimental outcomes, they highlight the importance of reliable online instrumentation for full-scale process optimization.

5.3 Uncertainty of results

Analytical precision at low concentrations presents the most significant challenge in this study, as both the phosphorus and micropollutant concentrations in the pilot effluents were close or below the LOQ values. For the pilot effluent values for micropollutants, almost all concentrations were below LOQ, requiring the use of 1/2 LOQ values for removal efficiency calculations based on literature guidelines (Sauter et al., 2021). Similarly, especially the PO₄-P concentrations were often below 0.05 mg/L, which is relatively low for quantitative analysis. Metropolilab has reported a 20 % measurement uncertainty for TP, TSP and PO₄-P concentrations, which is substantial at the target level of 0.1 mg/L TP. Additionally, sampling was constrained by the use of grab samples rather than composite samples for most parameters, except for micropollutant analyses where 6-hour composite samples were collected from the pilot effluents and 24-hour composite samples were collected from the Viikinmäki influent and effluent. Although grab sampling may not fully capture process dynamics, the composition of the Viikinmäki effluent is generally quite stable, which reduces the uncertainty of the results. If plant influent would have been used as the matrix, the importance of individual sample composition would have been considerably higher. Moreover, while some variation in Viikinmäki effluent composition was observed during the measurement period, this also reflects the natural variability in full-scale processes and therefore cannot be considered entirely as a source of experimental error.

5.4 Implementation considerations and recommendations

The EU Directive 2024/3019 requires minimum 80 % removal efficiency for at least six indicator substances calculated as an arithmetic mean through 48-hour composite samples under dry-weather conditions. The present study exceeded the 80 % removal limit substantially, however, only 600 BVs were operated during the pilot campaign. Additionally, 48-hour composite samples were not available and systematic selection of the sampling days to achieve dry-weather conditions was not possible. However, these variables are also present under full-scale operation and should be taken into account when planning future sampling strategies and compliance monitoring.

Despite the limitations presented in this study, the technical feasibility of full-scale implementation is supported by the consistently high removal rates for both phosphorus and micropollutants. The discontinuous pilot operation and non-optimized PAX dosing indicate that a full-scale system could potentially achieve similar or even better performance with optimized operational parameters. However, this study strongly supports the feasibility of meeting the EU Directive requirements and the 0.1 mg/L TP target at Viikinmäki WWTP with combined coagulation and GAC filtration. However, future research and pilot studies should provide continuous operation with studies extending to long-term GAC performance, breakthrough characteristics, and service life predictions. Moreover, as the current full-scale implementation plan at Viikinmäki WWTP involves integrating GAC filtration with ozonation, this would alter the overall process conditions and increase the need for additional pilot-scale experiments.

6 Conclusions

Phosphorus removal performance in both laboratory- and pilot-scale experiments demonstrated that the 0.1 mg/L TP target is achievable even at the already low TP concentrations of Viikinmäki effluent. Notably, GAC filtration without PAX dosing also achieved the target TP concentration, indicating inherent phosphorus removal capacity through GAC filtration alone. However, pilot-scale experiments showed the added value of coagulation, as after an initial stabilization period for the combined process, the PAX-GAC column consistently outperformed the GAC column for both TP and PO₄-P removal efficiency.

The PAX molar ratio of 20 Al:PO₄-P determined through flocculation jar tests and laboratory-scale column experiments proved to be suitable for floc formation while avoiding excessive filter clogging or head loss development. This molar ratio is notably higher than the conventional molar ratios of 4–5 reported in literature, highlighting the challenge of treating ultra-low phosphorus concentrations, where stoichiometric requirements differ from typical phosphorus removal applications.

Hydraulic performance and head losses remained manageable throughout the pilot operation, with backwash intervals of 1–2 days for both columns. The PAX-GAC column showed moderately higher head loss compared to GAC operation, but significant filter clogging or overflow issues did not occur. However, it must be emphasized that these backwash intervals are not directly comparable to continuous full-scale operation, as the pilot was operated only during working hours, allowing the GAC media to settle between operation. However, the composition of the backwash effluent supports the assumption that chemical coagulation was successful, as both TP and TSS concentrations were higher in the PAX-GAC backwash water compared to the GAC column.

EDS analysis and SEM imaging showed moderate differences in filter media composition between the two pilot columns after 600 BVs of operation. Aluminium content in the GAC media increased with PAX dosing compared to baseline regenerated GAC and GAC-only operation. Iron and phosphorus showed similar accumulation patterns, with PAX-dosed media demonstrating the highest weight % of both elements. SEM micrographs revealed that PAX dosing caused surface coating with metal precipitates that concealed the underlying carbon structure to some extent, while the GAC column showed less significant surface coverage with biofilm and organic residues. These findings suggest that metal-phosphate complexes form and accumulate on GAC surfaces especially during PAX dosing. However, the observed surface modifications remained relatively moderate after 600 BVs,

and the extent of further accumulation over extended operation cannot be assessed from these short-term results. Despite this surface accumulation, residual aluminium concentrations in the PAX-GAC effluent remained consistently low, while backwash effluent showed high aluminium concentrations. High aluminium concentrations in backwash effluent indicate efficient mechanical removal of aluminium-phosphate flocs during backwashing, preventing excessive buildup and maintaining filtration performance.

Micropollutant removal efficiency remained high (>90 %) for most of the EU Directive indicator substances in both GAC and PAX-GAC columns, with no significant difference between the two columns. Therefore, PAX dosing did not significantly affect micropollutant removal performance during the pilot-scale experiments despite the additional chemical load and floc accumulation in the filter bed. Additionally, UV₂₅₄ reduction exceeded 90 % in both columns, supporting the association of strong UV₂₅₄ reduction and efficient micropollutant removal performance. However, reliable quantitative correlation analysis could not be performed due to the limited data at removal efficiencies below 95 %, which is reported as a limiting value in other surrogate parameter studies.

Overall, this study demonstrated that combined PAX coagulation and GAC filtration can achieve both the EU Directive's micropollutant removal requirements (≥ 80 %) and the 0.1 mg/L effluent TP target under Finnish WWTP conditions. However, the high Al:PO₄-P molar ratio reflects the challenge of treating ultra-low phosphorus concentrations. Micropollutant removal remained above 90 % for most indicator substances regardless of PAX dosing, confirming that phosphorus removal and micropollutant adsorption operate mainly as parallel mechanisms. Despite moderate metal-phosphate accumulation on the PAX-GAC surface, residual aluminium in the effluent remained low while hydraulic performance remained stable. However, the pilot-scale campaign was limited to three months, thus, the results do not reflect the long-term impact of coagulant dosing on hydraulic performance, GAC saturation or the decrease in both micropollutant and phosphorus removal efficiency.

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A. GAC properties and design information (Filtrisorb 400®)

Note: The GAC used in this study was regenerated GAC from HSY's Vanhakaupunki water treatment plant, with an average mesh size of 8x30. As no detailed GAC specifications were available for the regenerated GAC, the commercial manufacturer's specifications for Filtrisorb® 400 (12x40 mesh), from which the GAC was originally regenerated, is presented in the tables below (Chemviron, 2022). Filtrisorb® 400 is a coal-based commercial GAC manufactured by Chemviron.

Typical properties	Filtrisorb® 400
Iodine number, min., mg/g	1050
Surface area, m ² /g	1050
Methylene blue number	300
Backwashed and drained bed density, kg/m ³	475
Floating content, wt%	0.1
Effective size, mm	0.7
Mean particle diameter, mm	1.1
Uniformity coefficient	1.7

Design information	Filtrisorb® 400
Superficial contact time	10–30 min
Bed depth	1–3 m
Linear velocity	5–20 m/h
Backwash bed expansion	20 %

B. Micropollutants analysed at Eurofins

Substance	CAS No	Category *	LOQ **	Measurement uncertainty	Accredited, Y/N	Method / standard
Amisulpride	71675-85-9	1	0.01 µg/L	50 %	No	EPA 1694:2007
Carbamazepine	298-46-4	1	0.005 µg/L	40 %	Yes	EPA 1694:2007
Citalopram (+ escitalopram)	59729-33-8	1	0.01 µg/L	50 %	Yes	EPA 1694:2007
Clarithromycin	81103-11-9	1	0.01 µg/L	49 %	Yes	EPA 1694:2007
Diclofenac	15307-86-5	1	0.005 µg/L	46 %	Yes	EPA 1694:2007
Hydrochlorothiazide	58-93-5	1	0.05 µg/L	49 %	Yes	EPA 1694:2007
Metoprolol	37350-58-6	1	0.005 µg/L	46 %	Yes	EPA 1694:2007
Venlafaxine	93413-69-5	1	0.005 µg/L	49 %	Yes	EPA 1694:2007
Benzotriazole	95-14-7	2	0.04 µg/L	45 %	Yes	EPA 1694:2007
Candesartan	139481-59-7	2	0.05 µg/L	50 %	No	EPA 1694:2007
Irbesartan	138402-11-6	2	0.01 µg/L	45 %	No	EPA 1694:2007
4-methylbenzotriazole and 5-methylbenzotriazole	29878-31-7 and 136-86-6	2	0.01 µg/L	55 %	Yes	EPA 1694:2007

* EU Directive 2024/3019 category.

** Limit of quantification. The LOQ values are provided for effluent wastewater matrix.

The analyses were conducted at the accredited Eurofins Environment Testing Finland Oy laboratory (SFS-EN ISO/IEC 17025:2017 FINAS T039). UV₂₅₄ absorbance was also measured with an internal method EF2044 (spectrophotometry), with an LOQ of 0.001 abs. The UV₂₅₄ method is not accredited.

C. Laboratory-scale sample preparation

Parameter	Sampling points *	Frequency	Laboratory	Sample type	Sample volume	Bottle	Instructions
TP, TSP, PO ₄ -P; Al, total and dissolved	Inf, flocculation tank, eff	10–15 BV	Metro polilab	Grab sample	100 mL	Clear plastic bottle	1 cm air gap, stored refrigerated
TP, PO ₄ -P	Inf, flocculation tank, eff	10–20 BV	Viikinmäki	Grab sample	100 mL	Beaker	Sample must be analysed at room temperature
Al, total	Inf, flocculation tank, eff	30–100 BV	Viikinmäki	Grab sample	100 mL	Beaker	Sample must be analysed at room temperature
UV ₂₅₄	Inf, flocculation tank, eff	10–20 BV	Viikinmäki	Grab sample	200 mL	Glass bottle	The sample should be analysed ASAP**

* Inf = laboratory column influent, eff = laboratory column effluent.

** As soon as practical.

Before each sampling, one sample volume was drained to waste.

The analyses at Viikinmäki laboratory were conducted immediately after sampling, therefore the samples were stored only in beakers.

D. Pilot-scale sample preparation

Parameter	Sampling points*	Frequency	Laboratory	Sample type	Sample volume	Bottle	Instructions
TP, TSP, PO ₄ -P; Al, total and dissolved; TSS	Pilot inf, flocculation tank, pilot eff, backwash eff	50–100 BV	Metropolilab	Grab sample	1000 mL	Clear plastic	1 cm air gap, stored refrigerated
TP, PO ₄ -P	Pilot inf, flocculation tank, pilot eff, backwash eff	100–200 BV	Viikinmäki	Grab sample	100 mL	Clear plastic	Sample must be analysed at room temperature
UV ₂₅₄	Pilot inf, flocculation tank, pilot eff, backwash eff	50–100 BV	Viikinmäki	Grab sample	200 mL	Glass	The sample should be analysed ASAP***
Micropollutants	Viikinmäki inf, pilot inf, pilot eff	70–100 BV	Eurofins	6- and 24-hour composite**	200 mL	Brown glass	1 cm air gap, stored refrigerated
UV ₂₅₄	Viikinmäki inf, pilot inf, pilot eff	70–100 BV	Eurofins	6- and 24-hour composite**	250 mL	Black plastic, light-protected	1 cm air gap, stored refrigerated, the sample should be analysed ASAP***

* Inf = influent, eff = effluent ** A 6-hour composite sample was prepared from the pilot effluents by collecting 1000 mL subsamples every hour and combining them in a plastic bucket. Viikinmäki influent and effluent samples were 24-hour composite samples. *** As soon as practical.

Before each sampling, one sample volume was drained to waste. Samples were taken after backwash.