Full-scale trials to achieve low total phosphorus in effluents from sewage treatment works

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Abstract

The tightening of phosphorus (P) standards has forced the UK water industry to identify options to improve P removal in sewage treatment works. This article presents results of 12-month trials testing three technologies at full-scale: a membrane bioreactor (MBR), a continuous backwash up-flow sand filter (CBUSF) and a high-rate compressible media filter (HRCMF). The aim of the trial was to determine the lowest total phosphorus (TP) concentrations that these systems can consistently achieve under stable operating conditions. MBR is a mature technology combining biological treatment with membrane filtration for solids removal. CBUSF uses granular media deep filtration as removal process while HRCMF uses a synthetic fibre compressible media to retain solids and both technologies are typically applied as tertiary treatments in combination with chemical P removal. The lowest TP effluent concentration was recorded for CBUSF (0.22 mgP/L) while the highest TP removal was recorded for MBR (95 ± 3 %). HRCMF delivered the poorest performance (32 ± 26 % TP removal, 1.7 mgP/L average TP effluent), attributed to limited chemical TP binding and solids removal under the conditions tested. Factors affecting P removal performance during the trial were the identification of the optimal coagulant dose to bind soluble P, the formation of solids that can be removed by the separation unit, insufficient reaction time for the coagulation process and the carryover of coagulant into the final effluent. The trials gave valuable insights to address the implementation of new technologies or upgrade existing assets' performance.

1. Introduction

The implementation of the Water Framework Directive [1] is driving an enhancement of the environmental status of UK water bodies and one of the implications is a general tightening of phosphorus (P) standards to reduce the phenomena of eutrophication [2]. The UK water companies are therefore faced with the challenge of enhancing the performance of their sewage treatment works during the next asset management programmes (AMPs) to meet total P (TP) consents of 0.5 mgP/l or lower [3]. This requirement represents a step-change for the UK industry compared to what was imposed in the past (generally effluent TP of 1 or 2 mgP/l), requiring the existing assets to be upgraded to comply with these new limits.

To share knowledge, inform investments for the next AMPs and achieve future regulatory discharge limits, a national collaborative programme between ten UK Water and Sewerage Companies (WaSCs) and the Environment Agency (EA) has been developed and delivered under the Chemical Investigation Programme 2 (CIP2) [4]. The collaborative programme, referred to as National Phosphorus Trial, had the specific aim of testing, at large scale, new technologies for P removal and optimisation of existing assets to achieve total P concentrations in final effluents equal or below 0.5 mg/L for optimisation trials or 0.1 mg/L for new technologies, based on annual averages of spot samples.

Conventional approaches to meet low P final effluent discharge limits are the use of enhanced biological P removal (EBPR) in secondary treatment processes [5,6] or the use of chemical coagulants to bound P into particulates [7,8], which are then removed by a solids separation system [9]. Rapid deep sand filtration, continuous filtration, cloth or micro-screen filtration are the most common separation processes associated with chemical P precipitation in final

polishing tertiary treatments stages [10,11]. The EBPR process is well established and commonly applied in many countries. Notwithstanding the wide implementation, limitations still exist in case of diluted wastewater or excessive nitrate loads in the anaerobic compartment. Competition between microorganisms also contributes to threaten the stability and reliability of EBPR, causing problems in meeting effluent consents [12].

Innovations targeting P removal are based on algae technology [13,14], adsorption into reactive media or electrochemical processes [15,16]. These new processes can achieve sustainable P removal and recovery from an environmental and an economic point of view [17]. In fact, in conventional approaches, P is recoverable only from sludge and solid residues [18] but at costs that are non-competitive for a marketable final product [8].

Severn Trent (ST), a water company based in Coventry, UK, identified three sites with three different technologies to be included in the collaborative National Phosphorus Trial, all operated at full scale: a membrane bioreactor (MBR), a continuous backwash up-flow sand filter (CBUSF) and a high-rate compressible media filter (HRCMF). These three technologies were selected together with other solutions of interest for the UK water sector and based on the availability of plants suitable for a full-scale trial [4].

A summary of the main characteristics of the three technologies under trial is reported in Table 1. MBR is a technology deployed for full treatment [19-22] while CBUSF and HRCMF are generally applied as tertiary treatment for final polishing, often combined with chemical dosing [23-27]. Coagulation and flocculation are fundamental processes for the implementation of P removal schemes based on chemical precipitation. Efficient chemical P removal not only relies on the definition of the optimal coagulant dose but also on the availability of time for the reactions to occur and the formation of flocs of size than can be effectively removed with a filtration process [28-30].

A variety of membrane systems can be considered to remove and recover P from wastewater [17]. Membrane bioreactors (MBR) represent a mature and widespread application of membrane technology for wastewater treatment [9]. Chemical P precipitation is typically performed in MBRs by dosing iron or aluminium salts into the activated sludge lanes before the membrane filtration step [8]. High dosages required to meet stringent effluent consents can increase membrane fouling, limit plant operation, and increase operating costs. Therefore, membrane units require the identification of an optimal balance between the flux that can be maintained on-site and the membrane fouling rate associated with the solids loads [31-33]. Effective chemical cleaning procedures and suitable screening systems to reduce fibre rags and trash accumulation are paramount to maintain the regular operation of MBR systems [34,35]. The overall aim of the trial tests was to determine what level of P removal and lowest concentrations the three systems can consistently achieve under stable operating conditions. This paper presents the key results and learnings from the trials at these three sites. A comparison discussion of the three technologies is presented detailing their performance and insight into the operational challenges associated with meeting low P permits in new or existing assets.

Table 1. Advantages and constraints of the three technologies under trial.

Technology	Advantages	Constrains
MBR	Small footprint Solid free effluents No settling problems No need for tertiary polishing or disinfection	Capital costs of membranes Need for membrane cleaning Energy costs for membrane operation and cleaning (air scouring)
CBUSF	Continuous operation Well known technology Possibility to incorporate nitrogen removal	Sensitive to variable influent flow
HRCMF	High filtration rates Small footprint Adjustable media porosity and bed depth	Need to change operative conditions if variable influent characteristics

2. Methodology and sites for the trial

The trial ran for 12 months, and 15 paired spot samples were collected from the influent and effluent of each technology. Sample collection started on April 2016 and finished in March 2017. Each sample was analysed for: total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), ammonium nitrogen (NH_4^+), total phosphorus (TP), soluble reactive phosphorus (SRP), total iron (TFe) and dissolved iron (DFe) and pH. Particulate phosphorus and particulate iron concentrations were calculated as the difference between TP and SRP. TSS, COD, BOD, NH_4^+ and TP were measured using standard methods [36]. Samples were filtered through 0.45 μm pore size syringe-drive filters to measure SRP and DFe. SRP concentration was determined by the molybdenum blue method [37]. TFe and DFe concentrations were analysed after acid digestion by an inductively coupled plasma-mass spectrometer (ICP-MS).

Removal efficiencies reported in the paper are calculated as averages of those obtained for each pair of influent and effluent samples.

A short optimisation phase was carried out for all the three sites to identify the best operational conditions that would enable compliance of low P effluent consents while avoiding the risk of breaching consents.

2.1 Membrane bioreactor

The trial investigated the capability of an MBR plant combined with a single point iron dosing system to achieve a TP final effluent concentration below 0.1 mgP/L. The MBR plant selected for the trial has a capacity to treat a population equivalent (PE) of 32,000, and the process flow diagram (PFD) is presented in Figure 1. The dry weather flow (DWF) of the plant is 7,420 m^3/d

(86 L/s) while flow to full treatment (FFT) is 195 L/s. The biological treatment is an activated sludge with anoxic/aerobic configuration. Sludge retention time (SRT) is 15 days and typical mixed liquor suspended solids (MLSS) concentration is 8,200 mgTSS/L. The filtration unit has an immersed configuration with membranes located in a separated tank where MLSS concentration is maintained at an average value of 10,200 mgTSS/L. The membranes on-site are GE WeeZeed 500 with a nominal pore size of 0.04 μm. The filtration system comprises six trains, each of them containing 12 cassettes and 16 modules per cassette. The total filtration area is 32,140.8 m^2. Transmembrane pressure varies between 55 kPa and 110 kPa while permeate flux varies between 10 L/m^{2}h and 25 L/m^{2}h.

The single point ferric sulphate dosing is located upfront of the activated sludge process and after the 1.5 mm screen. For the trial duration, the ferric sulphate dosing was controlled via an in-house developed feed-forward algorithm, which controlled the iron dose according to the orthophosphate (PO_4^{3-}) load entering the works. To calculate the PO_4^{3-} load, the algorithm used the PO_4^{3-} concentration of the crude wastewater, measured using an on-line P monitor, and the influent flow to the plant. The iron dose was calculated by converting the PO_4^{3-} load into a ferric sulphate dose using a Fe to P conversion ratio (gFe/gP). An initial optimisation phase for the trial resulted in setting the Fe to P ratio at 3.75 gFe/gP, and this value was kept until the end of the trial. This value corresponded to an average dose of 14 mgFe/L.

Samples for monitoring of the trial were collected from the influent of the plant downstream of the 3 mm screening (Influent samples) and the final effluent after membrane filtration (Effluent samples) (Figure 1).
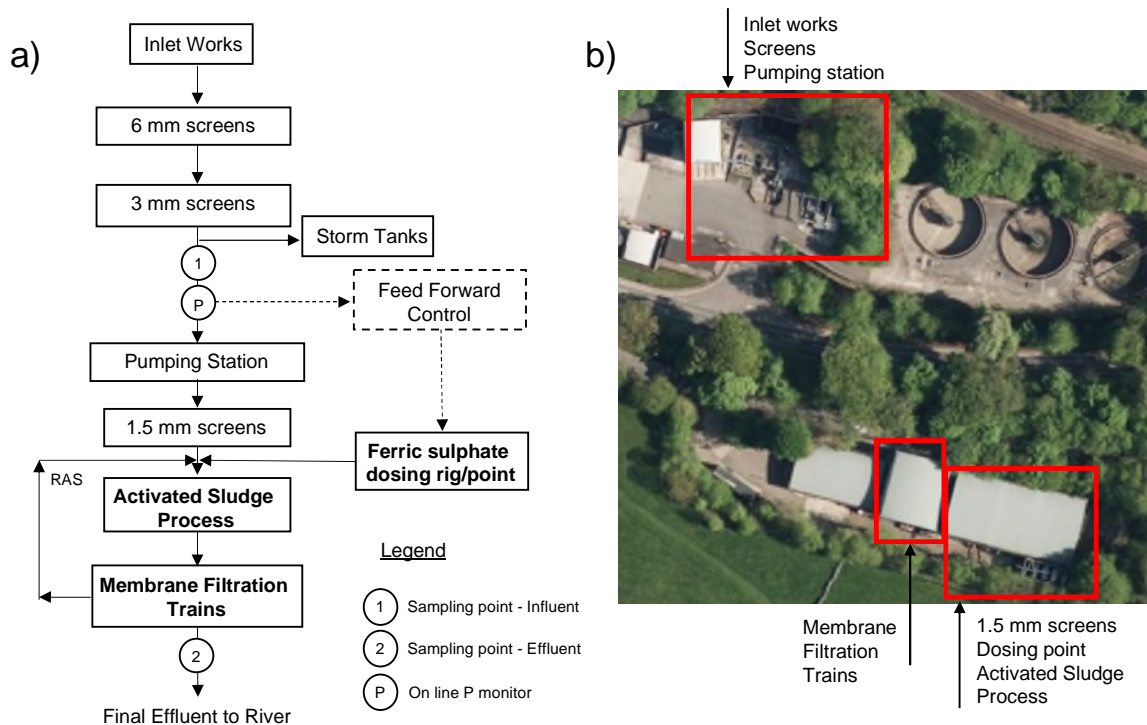
Figure 1. Process Flow Diagram of the Membrane Bioreactor plant (a) and an aerial view of the site (b)

2.2 Continuous backwash up-flow sand filter

The trial investigated the capability of a direct iron dosed CBUSF to achieve TP levels below 0.1 mgP/L. The filter unit is installed in a sewage treatment works of 11,000 PE characterised by a DWF of 2,600 m³/d (30L/s) and an FFT of 80 L/s. The PFD of the plant is shown in Figure 2. The CBUSF unit comprises five filters of 25 m³ each and treats the flow intercepted downstream of the humus tanks. The unit was designed to treat an average flow of 26.1 L/s and a maximum of 88 L/s. The CBUSF uses an up-flow moving bed of granular media to retain particles and colloids by the deep filtration process. Due to the dosing of ferric sulphate as a coagulant, P removal is a combination of chemical precipitation, particle filtration and adsorption of P onto the iron-coated sand grains [38]. The residues from the backwash and sand cleaning process are returned to the head of the works upstream to the primary sedimentation.

Ferric sulphate is dosed immediately upstream of the filter into an in-line static mixer, and the dose is proportional to the flow. Optimisation of the system led to an average dose of 12 mgFe/L.

The backwash water containing the iron-phosphorus precipitate is returned to the head of the works via the reject pump line, removed in primary sedimentation and disposed of with the primary sludge.

Samples for the monitoring of the trial were collected from the feed line of the CBUSF downstream of the pumping station and before the dosing point (Influent samples) and from the effluent of the filter (Effluent samples) (Figure 2).

2.3 High rage compressible media filter

The trial investigated the capability of an HRCMF to achieve an effluent P concentration below 0.5 mgP/L. The HRCMF full-scale unit is located in a sewage treatment plant serving a PE of 78,000 with a DWF of 16,150 m^3/d (187 L/s) and an FFT of 477 L/s (Figure 3a). The HRCMF consists of 4 filters working in parallel (Figure 3b). Each filter could treat an average flow of 50L/s. The filters use a synthetic fibre material as the filtration media, which is compressible and has a porosity of circa 90%. These synthetic media characteristics aim to adjust solids removal performance by changing the compression of the filtration media [17,38].

Only one filter of the four was used for the trial with an average flow reduced to 40 L/s to minimise the risk of non-compliance due to iron carry over into the final effluent. The filter was fitted with an additional ferric sulphate dosing system, and the dosing point was located in the rising main upstream of the unit on the influent to the filter. An in-line static mixer was installed directly after the dosing point to facilitate mixing and coagulation (Figure 3b). Ferric dosing was carried out continuously and only varied proportionally to the flow. Optimisation

of the unit led to a dose of 4 mgFe/L set to minimise the iron carryover. The media compression rate was set to 30% for the duration of the trial [39].

Samples for the monitoring of the trial were collected from the feed line of the HRCMF downstream of the pumping station and upfront of the dosing point (Influent samples) and the effluent of the filter (Effluent samples) (Figure 3b).
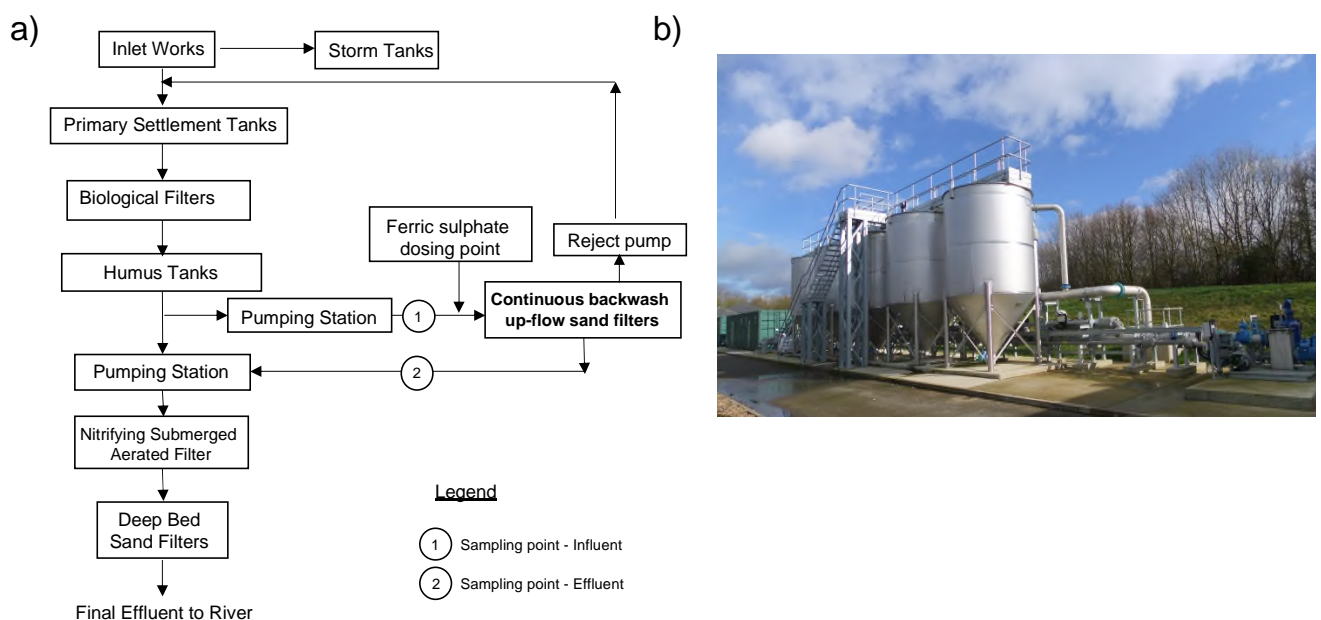

Figure 2. Process flow diagram of the plant where the continuous backwash up-flow sand filters are located (a) and view of the continuous backwash up-flow sand filters (b).
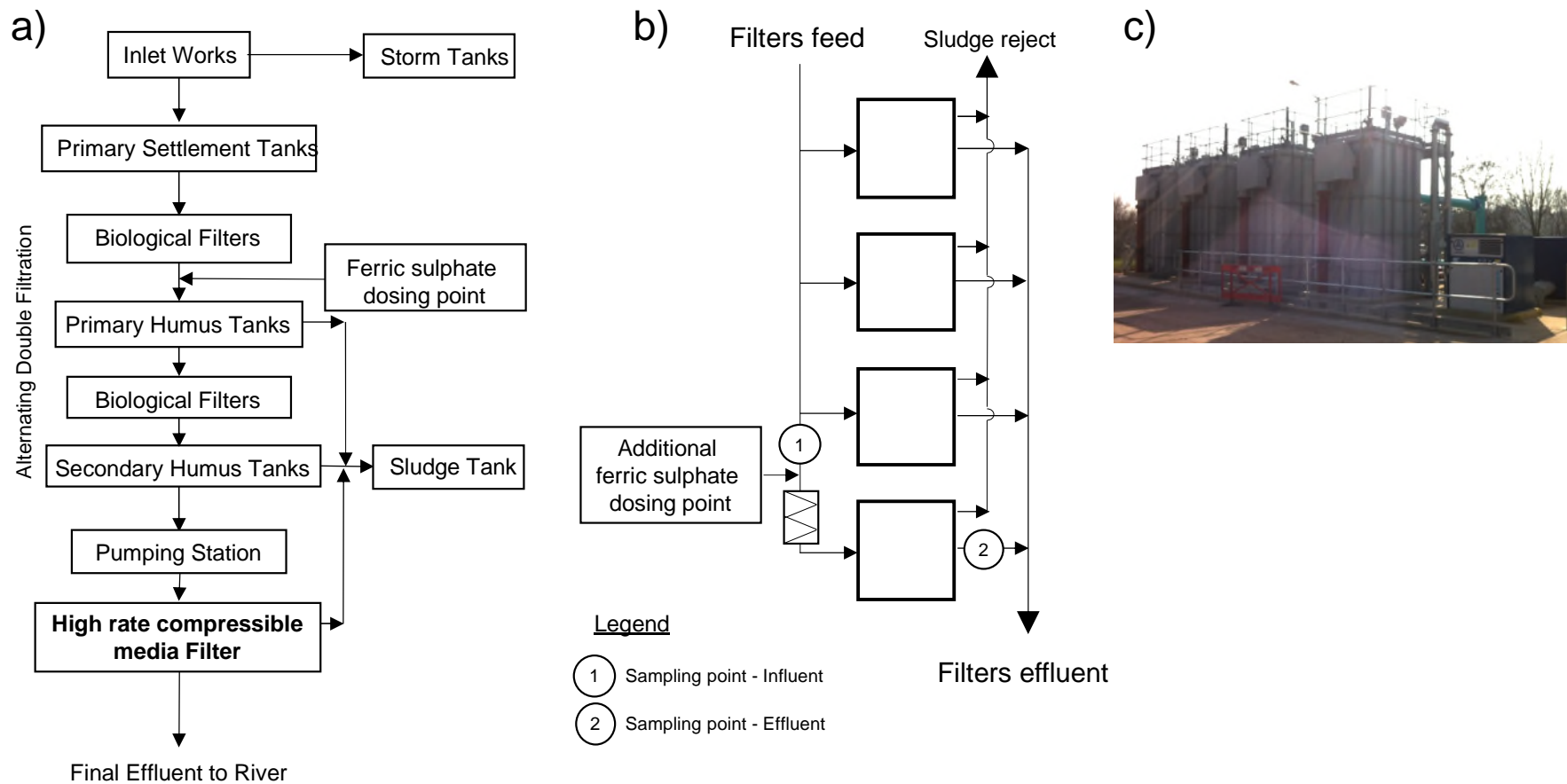
Figure 3. Process flow diagram of the plant where the high-rate compressible media filter is located (a), details of the location of the additional coagulant dosing point and static mixer upfront to the filter under investigation (b) and view of the high-rate compressible media filter (c).

3. Results and discussion

3.1. Processes performance

The three trials were characterised by different influent profiles (Table 2). The highest concentrations and highest variability for almost all parameters were observed for the MBR plant. The influent sampling point was located downstream of the 3-mm screening unit (Figure 1), and the profile is characteristic for crude sewage [38]. On the contrary, the influent sampling points for the CBUSF and HRCMF were immediately upfront of the treatment units and in both cases downstream of the preliminary, primary and secondary treatment works of the plants (Figure 2 and 3). Therefore, the profiles for these two sites are characteristic of secondary effluents with relatively low concentrations of organics and nutrients but still requiring a polishing step to meet future stringent final effluent consents. Despite a double filtration process upfront of the HRCMF, the influent to the unit was characterised by a relatively high TSS content and the highest influent concentration of TFe (Table 2). This may be due to the ferric sulphate dose upfront to the primary humus tank (Figure 3a). Solid particles bonded with the ferric coagulant are probably not removed by the sedimentation process in the humus tanks and escape with the secondary effluent. Average DFe was in fact below 0.5 mgFe/L, corresponding to about 5% of TFe, indicating that only iron bonded with particulate solids reached the HRCMF (Table 2).

The treatment performances of the main sanitary parameters (Table 2) evidence that the MBR plant achieved the highest removal for all parameters. This is due to the monitoring of a full train of processes, from crude influent to treated final effluent, and not only a single treatment step as for the two filtration systems. Results from the CBUSF and HRCMF indicate that both systems had a higher removal efficiency for BOD than COD. This is due to the further removal of some particulate biodegradable organics, not degraded in the biological steps and still present in the influent to the filtration units. COD removal was not as high as BOD removal

due to soluble but not biodegradable organics that are not removed by the coagulation or filtration steps, thus reducing the overall COD removal performance [23,24]. The filtration for both the HRCMF and CBUSF had no effects on ammonia concentration, this being a soluble compound. Dosing of ferric sulphate coagulant had limited or no impact on pH, that remained in all cases close to neutral conditions (Table 2).

Table 2. Average (± SD) influent and effluent concentrations and removal efficiencies for the three technologies under trial over a 12-month

sampling period.

	MBR			CBUSF			HRCMF		
	Influent	Effluent	Removal (%)	Influent	Effluent	Removal (%)	Influent	Effluent	Removal (%)
TSS (mg/L)	338 ± 278	2 ± 1	99 ± 1	15 ± 4	8 ± 5	40 ± 43	50 ± 64	24 ± 7	16 ± 49
COD (mgO$_2$/L)	579 ± 287	13 ± 5	97 ± 1	45 ± 8	20 ± 6	54 ± 11	62 ± 38	43 ± 7	21 ± 23
BOD (mgO$_2$/L)	228 ± 103	3 ± 1	99 ± 1	9 ± 2	3 ± 1	63 ± 11	13 ± 11	8 ± 3	26 ± 48
NH$_4^+$ (mgN/L)	26.9 ± 12.5	0.6 ± 0.8	97 ± 7	3.8 ± 2.1	3.2 ± 2.6	29 ± 33	1.1 ± 0.5	1.1 ± 0.5	-1 ± 28
TP (mgP/L)	9.18 ± 5.52	0.38 ± 0.21	95 ± 3	1.55 ± 0.31	0.22 ± 0.18	86 ± 10	3.39 ± 3.30	1.71 ± 0.53	32 ± 26
SRP (mgP/L)	3.75 ± 2.13	0.35 ± 0.21	89 ± 6	0.94 ± 0.35	0.05 ± 0.13	94 ± 16	0.91 ± 0.30	0.63 ± 0.31	29 ± 30
TFe (µgFe/L)	7577 ± 11433	80 ± 37	96 ± 3	1370 ± 540	1640 ± 784	-34 ± 68	8138 ± 34449	3834 ± 1798	-19 ± 82
DFe (µgFe/L)	726 ± 1118	60 ± 33	86 ± 8	296 ± 56	335 ± 88	-14 ± 28	471 ± 230	296 ± 99	-9 ± 61
pH	7.8 ± 0.4	7.1 ± 0.3	-	7.3 ± 0.1	7.3 ± 0.1	-	7.6 ± 0.1	7.6 ± 0.2	-

Only two of the three units under investigation achieved an average TP below 0.5 mgP/L during the trial period (MBR and CBUSF) but did not consistently achieve levels below 0.1 mgP/L. The MBR plant achieved an average TP effluent concentration of 0.38 mgP/L and average SRP level was 0.35 mgP/L. The TP removal efficiency was the highest among the three technologies with an average of 96% (Figure 4). This was obtained in a full-scale treatment plant with a contribution from both biological P uptake (but without an enhanced biological P removal established) of the activated sludge unit and chemical removal due to the dosing of iron sulphate combined with the highly efficient solids removal by the UF membranes. Experiences on P removal from MBR units in combination with chemical precipitation indicate that effluents concentrations in the range of 0.05 to 0.3 mgP/L could be achieved. These results were obtained from pilot-scale units to study the impact of high coagulant doses on membrane permeability [40,41] therefore at smaller scales and lower process variability if compared to the current study.

The CBUSF unit achieved TP and SRP effluent concentrations of 0.22 mgP/L and 0.05 mgP/L, respectively. The unit operates as a tertiary treatment process, and influent TP was the lowest of the three technologies assessed. Despite this, the filter required a dose of 12 mgFe/L, similar to the average coagulant dose of the MBR plant (14 mgFe/L). TSS removal was below 50%, and the unit achieved the highest SRP removal efficiency (Figure 4). Therefore, the dose was sufficient to bind most SRP in a particulate form, but this did not translate in similar removal for the TP. Studies of CUBSF pilot-scale units downstream of a moving bed biofilm reactor unit and aluminium based coagulant [25] or downstream of oxidation ditches with the dosage of a ferric coagulant [26] reported efficiencies and effluent concentration comparable to those observed in this trial. In both cases, average TP effluent concentrations were between 0.3 and 0.4 mgP/L while the soluble P fraction ranged between 0.019 to 0.177 mg/L with an average of 0.054 mg/L [25,26].

The comparability of the results from these studies suggests that MBR and CUBSF technologies can achieve consistent performance across different scales of application, influent qualities (i.e. synthetic or real wastewater) and complexity of operation [42].

The HRCMF only achieved an average effluent TP concentration of 1.71 mgP/l and SRP concentration was around 36% of TP (Table 2). Average TP and SRP removals were 32% and 28%, respectively (Figure 4) representing the lowest removal efficiencies of the three technologies. The unit was dosed with the lowest amount of coagulant, a ferric sulphate dose corresponding to 4 mgFe/L in the influent flow to the filter, ahead of the in-line static mixer (Figure 3b). This relatively low dose was due to a high carryover of iron through the filtration media that imposed a dose reduction to maintain compliance against final effluent consents. The average SRP effluent concentration for the HRCMF was circa 37% of TP, and TSS removal was around 16% (Table 2). To the best of our knowledge, experiences on integrating chemical dosing in HRCMF for P removal are limited. Only one study [43] reported data on P removal in an HRCMF unit at pilot scale with the use of alum and polyaluminium chloride (PACl) as coagulants. Effluent TP ranged between 1.15 and 1.44 mgTP/L, corresponding to an average removal of 35%, while TSS removal was 26% with an effluent TSS between 8 and 17 mg/L. These results were obtained using alum as coagulant at a dose of 30 mg/L and are comparable to those obtained in this study (Table 2) notwithstanding the different type of coagulant and the higher coagulant dose. The use of PACl allowed to achieve TP effluent concentrations below 0.5 mgP/L but with a coagulant dose of 70 mg/L. A comparison of results based on TSS removal indicates that these performances are on the lower end of the range of removal efficiencies reported for this technology (60 to 90%) [38,39]. These differences can be attributed to lower solids loads applied in other studies [38,39] suggesting a susceptibility of HRCMF to the characteristics and concentrations of the solids from upstream processes [43].
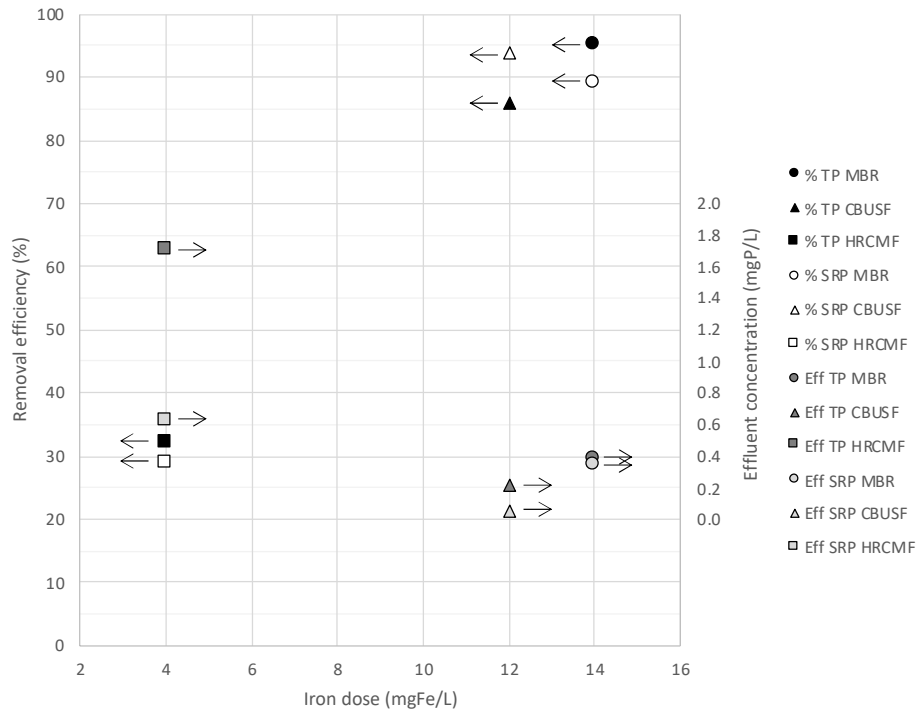
Figure 4. Average total phosphorus (TP) and soluble reactive phosphorus (SRP) removal efficiencies (left axis) and average effluent TP and SRP concentrations (right axis) versus iron dose as a coagulant for the three technologies under trial. Arrows indicate the reference axis for the data.

3.2. Effluent P profiles

The cumulative frequency curves in Figure 5 and the relationships between the fractions of P, the fractions of Fe and TSS presented in Figures 6 and 7 provide a deeper understanding and further insights of the specific features of the three technologies under trial.

3.2.1. MBR trial

The trends of the cumulative frequency curves for effluent TP and SRP of the MBR (Figure 5a), indicate that 50% of the samples were below a TP concentration of 0.3 mgP/L and 90% below 0.7 mgP/L. The curves for TP and SRP have similar shapes and almost overlap. This confirms that for the entire set of observations TP passing through the membrane barrier is made almost entirely of soluble P and that all particulate matter is rejected, recirculated in the system and wasted with the surplus sludge. Under the conditions of the MBR trial, 70% of effluent TP samples resulted below 0.5 mgTP/L while the annual average was below 0.3 mgTP/L. Effluent concentrations below 0.1 mgTP/L were, on the contrary, rarely achieved (Figure 5a). 50% of the samples resulted between 0.1 and 0.3 mgTP/L while a broader range was observed for the other 50% of results that varied between 0.3 and 1 mgTP/L.

As shown in Figure 5a, effluent TP for the MBR is only affected by the SRP fraction. There is, in fact, no correlation between TP and TSS (Figure 6a). At the same time, P and Fe particulate fractions are absent (Figure 7) due to the highly efficient solids removal process given by the UF membranes.

The results obtained during the MBR trial indicate that a higher dose of ferric sulphate could have allowed tighter effluent TP concentrations for the MBR plant by binding the residual SRP into a particulate form that the membrane can reject. Further optimisation would have been required to achieve higher P removal.

Experiences of P removal by chemical dosing in MBR units report very low P effluent concentrations (<0.05 mgP/L as TP) [40] but the large majority of data previously reported in literature refer to either lab-scale units [44] or pilot scale units [40,41,45] while full-scale plants' experiences are still limited [46,47]. The most common configuration for chemical P removal in a full-scale plant is the use of two dosing points, one upstream of the primary sedimentation and one after the biological treatment and upstream of tertiary treatments [40,41,48].

The dose of ferric coagulant in this trial was upfront of the activated sludge unit. The same configuration was reported in studies on chemical dosage for P removal in MBR units [41]. This solution implies that the coagulant enters a complex matrix like the mixed liquor and can be subject to transformation due to reducing (anoxic tank) or oxidative (aerobic tank) conditions and chemical compounds that can react with the coagulant, reducing its availability to remove P. The use of coagulant has been investigated as a strategy to reduce the impact of colloidal or soluble microbial products (SMP) on the membrane [40,41]. The competition between the chemical reaction of ferric with phosphorus species and other compounds able to react with the ferric coagulant combined with the variability of the influent TP and SRP concentrations (Table 2) can explain the reduced ability of the plant with chemical dosing to maintain a consistent effluent concentration close to the target value of 0.1 mgP/L for TP.

The dose of ferric coagulant used in the trial was in the range reported as having a limited impact on membrane fouling [40]. A key aspect of MBR technology is finding an optimal operational balance between the plants' fluxes, the energy requirements to maintain a low transmembrane pressure by scouring the membrane with air, and the chemical cleaning to recover initial permeability [19,20]. High solids load onto the membranes due to high doses of coagulants could increase the need to scour to maintain flux and the frequency of chemical membrane cleaning [20,41].
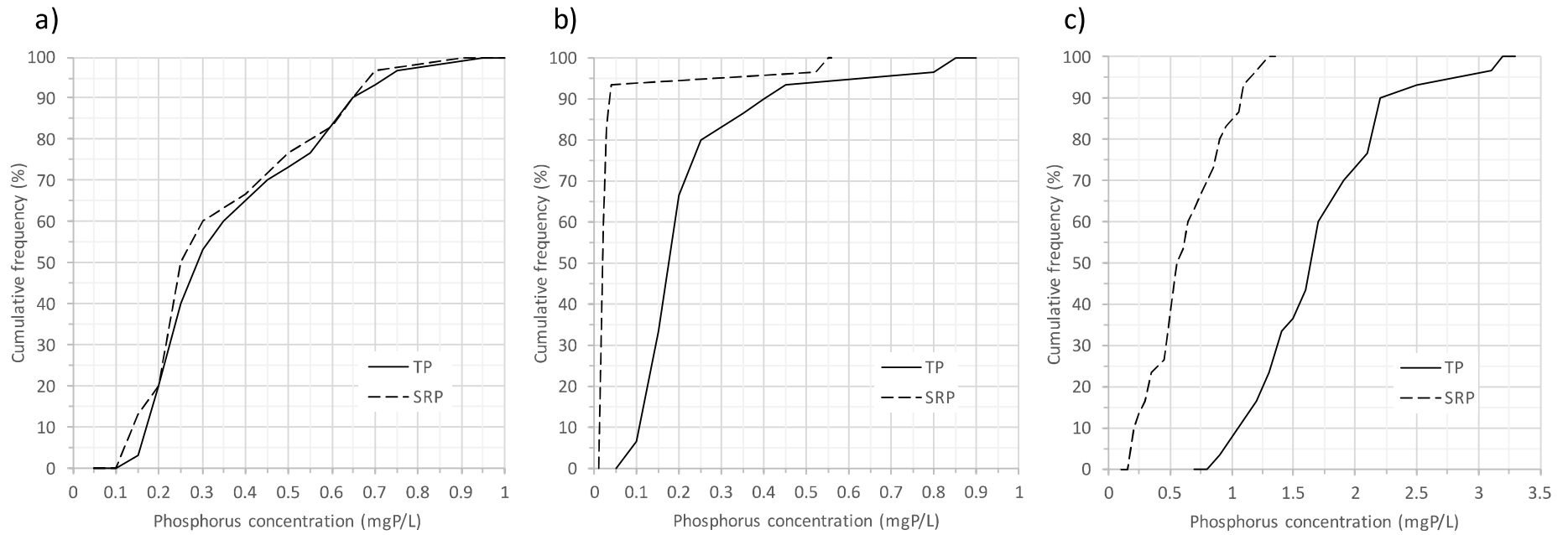
Figure 5. Cumulative frequency curves for total effluent phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations for the MBR (a), CBUSF (b) and HRCMF (c) sites

a) Effluent TP (mgP/L) vs Effluent TSS (mg/L)

b) Effluent TP (mgP/L) vs Effluent TFe (mg/L), y = 0.102x + 0.0082, R² = 0.8444

c) Effluent TFe (mgFe/L) vs Effluent TSS (mg/L), y = 0.1967x - 0.8977, R² = 0.6427
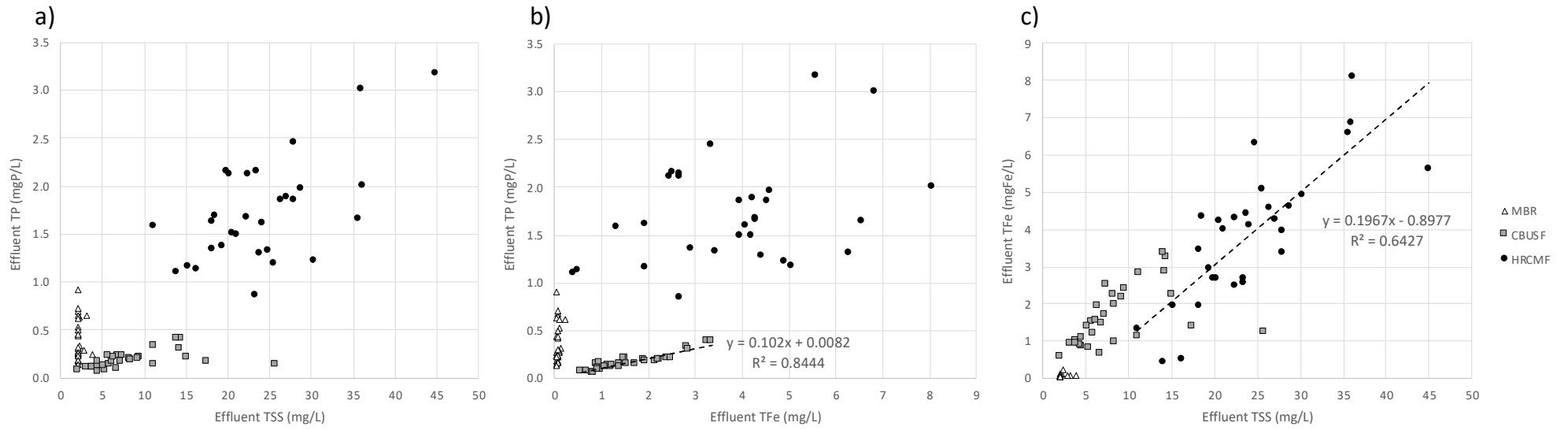
Legend: △ MBR, ▢ CBUSF, ● HRCMF

Figure 6. Relationship between TP and TSS (a), TP and TFe (b), TFe and TSS (c) for all the data obtained from the three technologies under trial.
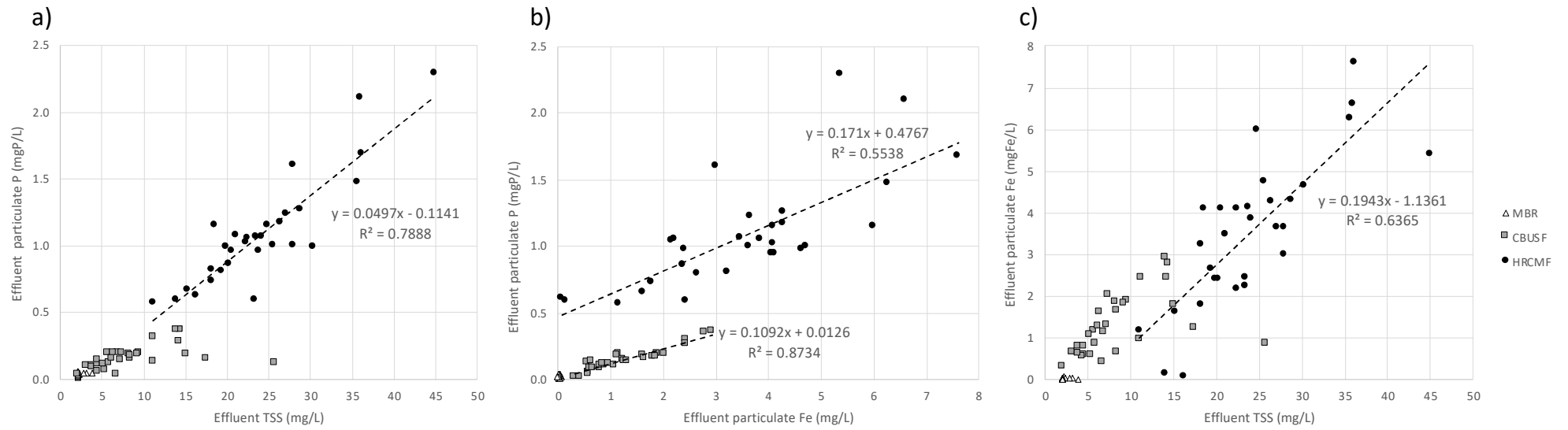
Figure 7. Relationship between particulate P and TSS (a), particulate P and particulate Fe (b), particulate Fe and TSS (c) for all the data obtained from the three technologies under trial.

3.2.2. CBUSF trial

The cumulative frequency curves for the CBUSF effluent (Figure 5b) highlight that almost 95% of SRB results were below 0.05 mgP/L. This confirms an effective chemical bonding of the soluble P fraction with solid particles. Another mechanism reported to contribute to P removal in CBUSF units is the coating of the filtration media by hydrous ferric oxide due to the ferric coagulant dose. This coating layer on the filter media's surface increases the reactivity with P compounds and enhances the removal of soluble fractions [49]. 50% of the samples had a TP concentration below 0.20 mgP/L, whereas 20% were between 0.25 and 0.90 mgP/L, indicating that a relatively small portion of the samples increased the overall average to 0.22 mgP/L. The gap between the two curves suggests that the particulate P fraction is for 95% of the time the main contributor of the effluent TP. This indicates that particle filtration was the limiting step to achieve lower TP effluent concentration and not the chemical dosage. The main contribution of particulate P to the effluent TP concentration was observed from pilot-scale studies for tertiary wastewater treatment [25,26]. Effluent particulate P fraction ranged between 93 to 99 % of TP confirming that low TP concentrations can be achieved by optimising solids removal mechanisms [25].

Correlations between TP and TSS (Figure 6a) and between particulate P and TSS (Figure 7a) are relatively low (R^2<0.5). This suggests that most solid P particles are removed by the filter even if some TSS still escape in the effluent. This can be explained by a sufficient dose of coagulant to react with P chemically and was confirmed by the low effluent concentrations of SRP and TFe observed for CBUSF (Table 2, Figure 5b). The excellent correlation between TP and TFe (Figure 6b) and their particulate fractions (Figure 7b) suggests that these particles are formed by P and Fe particles that did not form flocs big enough to be removed by the filter bed. This indicates that a further improvement of the flocculation process to create bigger or stronger flocs would have achieved an increase in TP removal and a reduction in TFe carryover.

Limitation on particle removal due to solid overload was also reported as another reason for the inability of CBUSF to achieve complete removal of TP [26]. The combination of the influent TSS load and the precipitation of dissolved solids with the coagulant dose can saturate the filter's ability to retain solid particles and fractions of TSS escape with the effluent. This effect can also be emphasised by influent flow fluctuations and variations in the influent characteristics leading to change coagulant dose [26]. Trial with the CBUSF indicates that the unit achieved high removal efficiencies and low P concentrations. Still, improvements in the formation of flocs or TSS removal could have delivered better performances for TP removal.

3.2.3. HRCMF trial

A wide range of effluent concentrations was observed for the SRP but particularly for the TP (Figure 5c) of HRCMF compared with the other two technologies. While SRP concentration varied between 0.4 and 1.3 mgP/L, TP ranged from 0.8 up to 3.3 mgP/L. TFe effluent concentration in the HRMCF trial was the highest among the three technologies (Figure 4). Both the wide variation of SRP and TP concentrations and the gap between the two curves show that the dosing system used before the HRMCF had limited success on chemically bounding the soluble fraction of P. At the same time, the filter showed limitations to remove the solids particles.

Results presented in Figures 6 and 7 for HRCMF confirm that the filter's performance was affected by these two aspects. Effluent TP is composed of about 40% soluble P (Table 2, Figure 5c) but a relatively low concentration of DFe (Table 2) indicating that the dose of coagulant was not sufficient to bound all P fractions. TP is therefore poorly correlated to TSS because of the large fraction composed of SRP. When data are cleaned from the contribution of SRP, and only particulate fractions are considered (Figure 7), a good correlation between particulate P and TSS emerges for HRCMF. This highlights the other aspect of the trial with the HRCMF.

The solid particles formed by the ferric coagulant dose are not big enough to be removed by the filtration unit even if the majority of the iron reacted with P and solids. This is confirmed by the correlations highlighted in Figures 7b and 7c showing that both particulate P and particulate Fe are part of the TSS in the effluent. These observations indicate that an improvement of HRCMF performance in P removal would have required a higher ferric dose and an improvement in either the flocculation process, form larger or stronger flocs, or in the filtration process to reduce the targeted size particles. Solid particles are removed in an HRCMF through interception and straining and these two mechanisms dependent on particle size and concentration [38-39]. Therefore, constraints on the possibility to affect particle agglomeration can limit the ability to achieve desired removal performance for this technology [43].

Results from HMRCF indicate that the filter's performance in removing P was affected by non-optimal conditions both for the coagulation and flocculation process that resulted in a limited TP and TSS removals. Data suggest that the coagulant dose is not sufficient to bind all SRP into a particulate form and that the coagulation process could not form solid agglomerates big enough to be retained by the compressible media. Due to site constraints on the dosing point location, a short contact time of only 1 minute was available for the dosed coagulant to react with the P and solids to form aggregates that the filter could remove.

The need for high coagulant doses to achieve low TP concentrations was observed during a pilot-scale trial of an HRCMF unit for tertiary treatment [43. TP below 0.5 mgP/L and almost complete orthophosphate removal were only achieved with a dose of 70 mg/L of PACl (9.5% aluminium based on weight). Still, this dose strongly reduced the filter's run time due to an excess of solids load and was indicated as not suitable for regular operation. Whilst doses between 15 and 50 mg/L did not affect running time of the filter, they had no significant effects on P removal and only contributed to improving TSS removal performance. These results were

obtained with a contact time between the coagulant and the flow of 2 minutes while mixing was minimal [43]. On the contrary in the present full-scale trial mixing was maximised by using an on-line mixer but contact time was of only 1 minute, which highlights the crucial role of reaction time for the formation of large flocs coagulation and flocculation once mixing is optimised [50]. No details were reported on the carryover of coagulants during the trial [43].

3.3 Insights from the full-scale trials

The trials confirmed that a critical aspect of a chemical P removal is the formation of solids particles that a solids separation unit can remove. The effluent from the HRCMF was characterised by the highest TFe and TSS concentrations, even though the coagulant dose was the lowest. On the contrary, for the technologies with a more efficient TSS removal (MBR 99% and CBSUF 40%, Table 2) TFe concentrations in the effluent were lower, notwithstanding the higher coagulant doses.

Insufficient reaction time before the solid removal stage was the reason for the high iron carryover in the HRCMF. To compare, the CBUSF did not have a very high TSS removal efficiency (40%) but delivered a better P removal and a lower iron carryover that the HRCMF (Table 2). Soluble iron carryover was comparable for CBUSF and HRCMF (Table 2), showing that identifying the optimal dose of coagulant for complete reaction of the Fe with P (and solids) is challenging. The trial also showed that when a highly efficient solids rejection system is used (MBR), iron carryover was limited only to the soluble fraction that did not react with P or with other solids to form flocs.

Iron carryover is an aspect of particular concern when using iron-based coagulants for P removal. An excessive release of iron into the final effluent could be due to a higher dose than required to react with the available P, non-optimal conditions for coagulation and flocculation (not enough time or mixing) or a low solids removal efficiency [28,51], with the consequence

of a possible breach of the regulatory iron consents for the effluent discharge [52] or for other metals limits [53,54]. Despite the operational importance of avoiding coagulant carryover to effluents, limited or no data are reported about this aspect indicating the need for further investigation.

The requirements for a successful chemical P removal process are, therefore (i) an adequate dose to chemically bind all P particles and reduce iron carryover, (ii) enough reaction time for the flocculation process to form flocs of sizes that can be separated, (iii) an efficient solids separation unit downstream the dosing point.

Trials performed at full scale often pose challenges to operators and managers in defining new optimal conditions while maintaining the works operational and meeting required effluent consents. These studies were no exceptions, with some lessons learnt while delivering the trials for the collaborative programme. The trial at the MBR site highlighted the need for robust operation of on-line monitors for the correct implementation of a feed-forward control of coagulant dosing. Monitoring the quality of crude sewage (e.g. PO_4^{3-} concentration) can be challenging due to the automated analysers' harsh operational conditions. To illustrate, high variability in analyte concentrations such as that found in crude sewage requires frequent reading cycles increasing the operational stress on the on-line monitors; the large presence of trash or rags can clog sampling lines compromising sample collection; the usual deep location of inlet works requires extended sampling lines between the sampling point and the location of the analyser, which can compromise the reliability of the readings. The trial at the MBR site involved using a feed-forward algorithm relying on continuous PO_4^{3-} concentration data of crude sewage samples (Figure 1). This required a bespoke installation design to overcome the long distance between the sampling point and the analyser, as well as frequent control and maintenance of the automated unit to maintain the operation and reliability of the readings.

The HRCMF trial evidenced that retrofitting a dosing system into an existing asset could limit the coagulation and flocculation processes' performance. The plant's configuration and the space available for the trial limited the possibility of installing a coagulation and flocculation chamber to optimise flocs formation. Enhanced mixing was obtained by installing an in-line static mixer for contacting the coagulant and wastewater (Figure 3b). However, the volume available for the flocculation (an empty part of the HRCMF unit) was insufficient in providing the required retention time for flocculation.

High flow variation can be a frequent characteristic of small sewage treatment works. This variation can have substantial impacts on processes relying on specific operational conditions, such as up-flow velocity, chemical dosing defined on the base of influent characteristics or solid loads [5]. High variations of flow can influence the flux that a unit has to treat, dilution due to storm events can either reduce the load of compounds to be chemically removed (e.g. P) [55,56], or increase the load of solids due to a higher carryover from previous treatments (e.g. solids escape from settling tanks) [38,57]. The CBUSF trial highlighted that this technology would have performed better with a more stable flow. Flow variability reduced the ability of the filters to deliver a low P effluent consistently. Further optimisation of the technology required more significant operator input than expected, especially to define how to operate the process during high flow events best and establish the operating and control philosophy adjustments needed in the cut in/out set points to avoid excessive flow variations.

Process selection is often a site-specific exercise that has to include various factors to identify the preferred solution. Each technology has specific advantages that can guide the selection process to achieve treatment targets for new plants or retrofitting and upgrading schemes. Constrains or limitations also exist for methods and systems. Design teams are sometimes faced with the challenge of making decisions based on limited information or experiences not directly comparable, particularly for new technologies. Similarly, operational teams must identify and

maintain the best running conditions to meet the treatment performance at the lowest possible costs. The National P trial's collaborative nature can help address these challenges and provide design and operational teams with the information needed to develop and deliver innovative schemes and find solutions to tackle the P challenge.

4. Conclusions

The results from the trials' experiences indicated that MBR and CBUSF can achieve effluent TP levels below 0.5 mgP/L and that further optimisation of the dosage of coagulant and solids removal could enable these processes to achieve a target of 0.1 mgP/L. The trial with the HRMCF highlighted how iron carryover represents an important limitation on trying to achieve low P targets as it can threaten the effluent consent limits for other parameters (i.e. metals). Other challenges in implementing new schemes to meet tighter P consents are the constraints and specific characteristics of the site (i.e. space availability and flow variations) and the reliability of monitoring systems.

Sharing the outcome and experiences from the National P Trial on design, installation and operation of technologies at relevant scales, can help to speed up the implementation of specific schemes to achieve new and tighter effluent consents in the next AMP periods and contribute to attaining enhanced environmental quality standards for the UK water bodies.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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