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Optimization of coagulation/flocculation for phosphorus removal from activated sludge effluent discharge using an online charge analyzing system titrator (CAST)

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ABSTRACT

Coagulant dosing is traditionally based upon jar-tests or operator experience, resulting in either overdosing or insufficient dosing. In this study, we assess the feasibility of a new coagulant dose control instrument, the online charge-based automatic titration system, charge analyzing system with titrator (CAST), to determine coagulant dosages from active sludge effluent discharge in municipal wastewater treatment plants. Results show that treated total phosphorous (TP) concentrations were successfully lowered to less than the site's 0.5 mg/L limit indicator level. These results suggest that the CAST system to be a very useful automated chemical dosing instrument for the coagulation/flocculation process in wastewater treatment plants (WWTPs).

1. Introduction

Today, wastewater treatment plants (WWTPs) in South Korea must reduce phosphorus (P) levels to meet increasingly stringent environmental regulations. The environmental initiatives of the Ministry of Environment (MOE), as well as those of individual treatment plants, require management response. Current total phosphorus discharge limits for many WWTPs range from 0.5 mg/L (Level 3) to 0.2 mg/L (Level 1). Phosphorus in domestic wastewater is an important macronutrient for plant and microorganism growth. However, the discharge of large quantities of this nutrient into natural receiving sources increases algae growth and causes the eutrophication of lakes and streams [1,2]. While algae may grow at PO_4^{3-} levels as low as 0.05 mg/L, its growth can be inhibited at PO_4^{3-} levels well below 0.5 mg/L [3]. But phosphorus concentrations in secondary effluents are usually within the range of 3–7 mg/L, and consist mostly of orthophosphate and about 1 mg/L of organic phosphorus [1,4]. Therefore, the concentration of phosphorus in secondary wastewater must be reduced to prevent algal bloom.

Phosphorus removal techniques fall into three main categories: physical, chemical and biological [5]. Chemical removal techniques using metal salts are some of the most reliable and well-established processes [6]. The most common chemical technique removes phosphate by precipitation. Precipitation processes are capable of removing at least 90–95% of phosphorus at a reasonable cost [7]. Numerous substances have been used as coagulants, including $Al_2(SO_4)_3{\cdot}18H_2O$, $FeCl_3{\cdot}6H_2O$, $Fe_2(SO_4)_3$, $FeSO_4{\cdot}7H_2O$, and $Ca(OH)_2$. Recent studies have reported the optimal coagulation conditions to maximize $Al(OH)_3$ formation in a bulk solution [8,9], as shown Eqs. (1) and (2)

$$Al^{3+} + H_2O \rightarrow Al(OH)^{2+} + H^+ (pH4-5) \tag{1}$$

$$Al^{3+} + 3OH^- \rightarrow Al(OH)_3 (pH6-7) \tag{2}$$

WWTPs are now facing increased pressure to produce higher quality treated wastewater at a lower cost. The coagulation–flocculation process is a major step forward in reducing phosphorus loading, and allowing the removal of colloidal particles [10]. The main difficulty in this process is to determine the optimum coagulant dosage in relation to the influent of raw wastewater. Excessive coagulant dosing increases treatment costs and public health risks, while under dosing leads to a failure to meet the water

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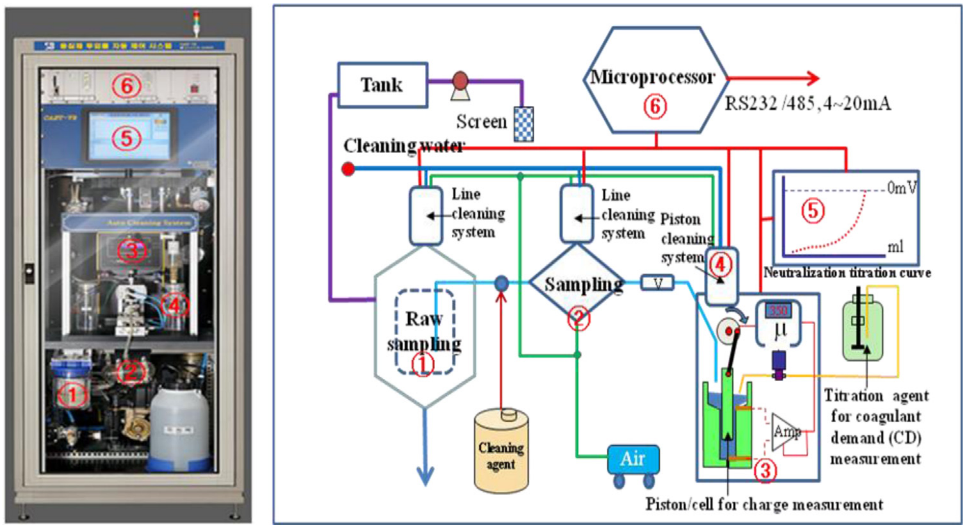


Fig. 1. Sam Bo Scientific's CAST system: (1) auto sampling device, (2) sample transfer device, (3) measurement and charge neutralization titrator, (4) auto cleaning unit, (5) display, and (6) control unit.

quality targets and a less efficient operation of the wastewater treatment plant [10,11].

This paper presents a 140 m^3/d pilot for phosphorus removal using a coagulation process with an online real-time charge analyzing system with titrator (CAST) system to control coagulant dosing. The online CAST coagulant dose control system allows the coupling of real-time colloid charge titration with on-line feed forward and feedback control. This system promises to measure coagulant or cationic demand (CD) volume over time in highly fluctuating wastewater quality conditions. The CAST system is a continuous sampling, on-line instrument that enables the treatment plant operator to know precisely and at all times the optimum coagulant dosage. The purpose of this project was to test the performance of the online CAST system in maintaining a total phosphates limit of 0.5 mg/L in discharge wastewater.

2. Materials and methods

2.1. Activated sludge effluent (ASE)

The treated domestic wastewater used in the present work is ASE from the Nanji WWTP in Goyang city, Gyeong-gi province, Korea which has a treatment capacity of 1,000,000 m^3/d [12]. The plant treats wastewater collected from the northeastern part of Seoul, and accounts for 17% of Seoul's total wastewater treated. The treatment process of the full-scale plant includes a conventional activated sludge process and a biological nitrogen and phosphorus removal process. To enhance phosphorus removal and keep the TP concentration of the secondary effluent below 0.5 mg/L, inorganic coagulants are added into the aeration tank. The activated-sludge effluent was collected from the plant from September 2012 to December 2012 between 00:00 h and 24:00 h using an auto sampler. Each time a sample was collected, the flow rate was measured with a flow meter.

2.2. CAST system

Developed by Sam Bo Scientific Co., Ltd, the CAST system consists of six key parts as shown in Fig. 1. This on-line charge analyzer with a titrator can monitor and measure chemical (coagulant) demand by measuring charge neutralization, and has chemical dosing control functions for the coagulation/flocculation processes.

The CAST system provides accurate and precise chemical doses, as well as acting as an automatic dose monitoring and verification system. A wastewater sample is titrated into the cylinder cell of the CAST system. When the Teflon piston reciprocates by moving up and down, a streaming current (SC) is measured by two gold electrodes at the upper and lower ends of the cylinder cell.

The measurement, known as the SC or charge value, is recorded in mV units, and is normally displayed in a range between −2000 and +2000 mV. Typically, 10–15 mL of the water sample is titrated into the cylinder cell, and 10–50 μL of cationic polyelectrolyte (coagulant), to determine the CD, is injected into the measuring cell every 3–30 s by dynamic titration until electrical neutrality (0 mV) is reached. The microprocessor controller calculates a target polymer dose based on the SC and the CD measurement for charge neutralization with a coagulant and an internal algorithm, as shown in Fig. 2.

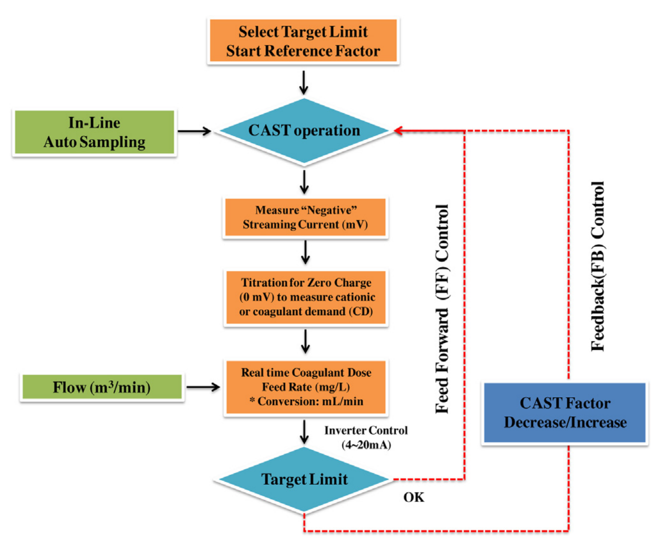


Fig. 2. Logic diagram for controlling coagulant dosage in the CAST system.

When considering the conversion of coagulant dosage, the negative charge distribution in the bulk solution can be interpreted based on the titrant dose ratio [13,14]. The coagulant dose can be calculated according to the SCD titration ratio, as shown in Eq. (3).

$$K_{amp} = \frac{i_M}{i} \tag{3}$$

where K_{amp} is an amplifier constant, i is conventional titrant dose which were already known sample and coagulant dose (mg/L), and i_M is the measured titrant dose in the unknown sample. Eq. (3) indicates the ratio of titrant dose of an unknown sample (i_M) divided by conventional titrant dose (i).

When applied to a sample of an unknown influent, the optimal coagulant dosage is expressed as Eq. (4):

$$C_{dose} = K_{amp} \times J_{condition} \tag{4}$$

where C_{dose} is the optimal coagulant dosage of unknown sample, and J condition is the jar test condition which was already known turbidity and coagulant dose. Based on Eq. (4), the coagulant dose was calculated according to the sample concentration.

As flow rate and water quality vary, the system continuously recalculates the optimum coagulant dosage to maintain optimal water quality and varies the coagulant feed accordingly. Optimum coagulant dosage is reestablished within 15 min based on changes in flow or the total charge of the suspended materials. The coagulant dosage is determined from the feed-forward (FF) control and the feedback (FB) factor adjustment. Initially, the CAST system provides an FF control that assures a continuously accurate coagulant dosage to meet the target limit.

If the value is above the required limit under the CAST's controlled factor, the CAST controller recalculates the coagulant dosage to meet the target limit by an FB "CAST Factor" control. The CD value that corresponds to the optimum dosage is typically determined by jar tests during the start-up test. In operation, the CAST Factor can be adjusted upwards or downwards, allowing the system to be fine-tuned for specific conditions or requirements.

2.3. CAST-based coagulation/flocculation system

Fig. 3 shows a schematic diagram of the CAST-based coagulation/flocculation system used for phosphorus removal from the activated-sludge effluent wastewater. A typical coagulation/flocculation system consists of an influent pump, a raw water tank, the CAST unit with an on-line sampler and polymer metering pump, a coagulation/flocculation tank, and a clarifier tank.

There were two units (units 1 and 2) in this experiment; unit 1 had the CAST system and unit 2 had control system using jar testing. In each of the tests, activated-sludge effluent was pumped into the raw water tank. Fig. 3 shows the setup of the coagulation/flocculation–sedimentation process for the coagulant dosage control experiment. The main components were the rapid mixing tank (capacity 152 L, residence time 1 min), the flocculator (1656 L, 35 min), and the sedimentation tank (30 L, 30 min). After the settling period, samples were taken and analyzed immediately. This wastewater sample was then put directly into the pilot system without any pretreatment screening or pH control.

2.4. Chemicals

In case of low alkalinity wastewater in the Nanji WWTP, P removal by coagulation is very difficult because of the rapidly changing pH after the coagulant has been added [1,12]. Ferric chloride or alum may not provide proper floc formation, so a high basicity polymer, such as polyaluminum hydroxychloride (PACl) or Poly Aluminum Hydroxy Chloro Sulfate (PAHCS) may be considered [15].

The chemical used as the coagulant in this research was PAHCS (12.5% Al_2O_3 with a basicity of 70%, Samgu Chemical Co., Korea) which is commonly used for phosphorus removal. In previous studies PAHCS has achieved much better results in removing total phosphorus, and lowering turbidity and dissolved organic carbon (DOC) than PAC and alum [16,17].

The PAHCS coagulant used in this study has been shown to confirm that the Al_{13} species has a higher positive charge and is the most effective polymeric Al species for water and wastewater treatment [18]. It does not require the addition of an alkali to raw water for coagulation, and is much less sensitive to pH, operating within the pH 4.5–9.5 range. Neither is the mixing time critical. The floc is tougher and, if substituted for hydrolyzing metallic salts, it may be possible to reduce the dosage and avoid using any coagulant aid [15,19].

2.5. Analysis

Samples were taken with a Hach autosampler (SD900) and kept in plastic containers (high density polyethylene HDPE-volume of 40 L), then transferred to the laboratory and kept at 4 °C until used. Biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), total nitrogen (TN), and TP were analyzed using a Hach spectrophotometer. Other parameters in the samples were analyzed by the standard methods detailed in American Public Health Association (APHA) (2005). Raw and coagulated samples were also analyzed for their pH, BOD, COD, TN, and TP according to the standard methods (APHA, 2005). We determined COD using the closed reflux, calorimetric method, including digestion at 150 °C for 2 h in COD vials followed by a spectrophotometer reading at 530 nm (APHA, 2005). The pH was measured using a digital pH meter (HANNA, HI 991003 Sensor).

2.6. Statistical analysis

The statistical analysis in this study was conducted using the statistical program MINITAB for Windows Version 14.0. The values for TP percentage removal for each influent and effluent concentration pair were compared statistically using a paired t-test and two-sample t-test. The paired t-test was used to compare the mean values of TP reduction for the two systems by coagulant dose type or initial condition coagulant dosage. The data could not be paired for the CAST operation factor test because no matching dates were available (Table 1). An F-test was used to determine whether variances could be assumed to be equal, and an independent two sample t-test was used to compare the CAST operation factor means.

3. Results and discussion

3.1. Raw characteristics

The city of Seoul is currently planning to expand their phosphorous treatment process to meet the new effluent phosphorous standard of 0.5 mg/L. The WWTP's current treatment process consists of headworks, primary settling, conventional activated sludge, and secondary clarification. The city initiated a phosphorus control study to determine what steps were needed to meet the new phosphorus limit requirement, and also took into account many other considerations. There was limited site availability for any expansion of the WWTP. For 3 months from 1 September to 2 December 2, water quality data was collected every 2–3 days. The raw, primary and secondary wastewater characteristics are given in Table 2.

The characteristics of the influent wastewater samples were: BOD 109–421 (209.2 ± 51) mg/L, COD 65–193 (101.3 ± 25) mg/L,

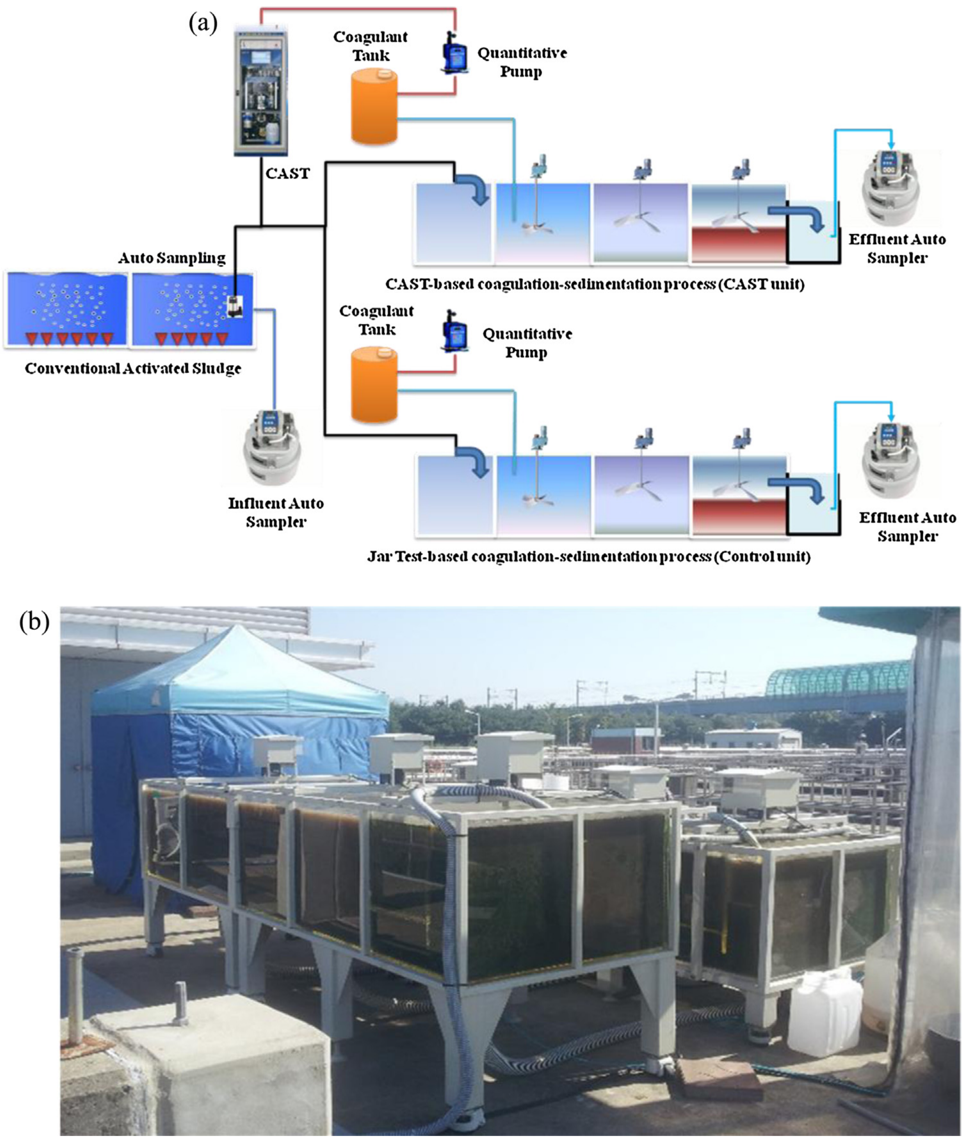


Fig. 3. Setup of the CAST-based and jar test-based chemical coagulation/flocculation–sedimentation process.

SS 98–300 (183.9 ± 44) mg/L, TP 3.5–5.8 (4.26 ± 0.47) mg/L, and TN 25.1–44.8 (37.4 ± 5.3) mg/L. The influent temperature varied from 12 to 26 °C and the pH varied between 6.8 and 7.2. The influent data presented in Table 2 show an influent COD/BOD, COD/TN and BOD/TN ratio of 0.48, 2.73 and 5.65, this means that the organic material present is easily biologically degradable and the COD/T–N ratio of 2.73 is very low, meaning that easily degradable COD will be limiting for full denitrification. The high COD/T–P ratio, 23.7, should favor Bio-P removal. However, the limited nitrogen removal in the main tank renders the RAS with a high nitrate concentration. The target limit for the total phosphorus effluent of this site was lowered from 2 mg/L to 0.5 mg/L. The existing facility could only produce a secondary effluent with a TP concentration of 0.6–2.2 mg/L by adding 5–7 mg/L PAHCS in advance of the secondary clarifiers. The average secondary effluent concentration of total phosphorus was reported to be about 1.19 ± 0.23 mg/L.

Typically, secondary treatment can remove only 1–2 mg/L of phosphorous, so a large excess is necessarily discharged in the final effluent, causing eutrophication in surface waters [1–4]. Since new legislation mandates a maximum concentration of P discharges into surface water of 0.5 mg/L, an operational goal is to keep total phosphorus levels in the final effluent under 0.3 mg/L to ensure that the 0.5 mg/L permit limitation is met consistently. Thus, an optimal coagulation/flocculation process will use an online chemical addition in advance of the secondary clarifiers to reduce total phosphorus concentration and maintain levels below the 0.5 mg/L permit limitation.

Table 1
Field test dates and statistical analysis methods used.

Items	Start	End	Statistical analysis
Coagulant dose type	11/08/2012	12/10/2012	Paired *t*-test[a]
CAST Factor control	–	–	Two-sample *t*-test[b]
- Factor = 13	11/08/2012	11/30/2012	
- Factor = 10	11/30/2012	12/10/2012	
Initial coagulant dose[c]	12/01/2012	12/10/2012	Paired *t*-test[a]

[a] The paired *t*-test indicated a significant difference at the 95% confidence level between the data-pair values in the control and CAST systems.
[b] The two sample *t*-test indicated a significant difference at the 95% confidence level between the independent data values by controlling the CAST operation factor.
[c] Initial condition of coagulant dosage in the control system with a constant 10 mg/L feed of PAHCS dosage and in the CAST system with real-time dosing by controlling operation factor = 10 (Factor 10 = an initial level of 10 mg/L of PAHCS).

Table 2
Changes influent and effluent values in the municipal wastewater site.

Constituent	*N*	Influent	Primary effluent	Secondary effluent
pH	61	7 ± 0.06 (6.8, 7.2)	6.94 ± 0.07 (6.8, 7.2)	6.65 ± 0.12 (6.4, 6.9)
BOD (mg/L)	61	209.2 ± 51 (109, 421)	106.4 ± 15.3 (62, 156)	7.03 ± 0.55 (5.5, 8.3)
COD (mg/L)	61	101.3 ± 25 (65, 193)	52.5 ± 9.64 (40, 83)	8.12 ± 0.23 (7.1, 8.7)
SS (mg/L)	61	183.9 ± 44 (98, 300)	54.72 ± 20.3 (28, 120)	2.43 ± 0.72 (0.7, 4.2)
TP (mg/L)	61	4.26 ± 0.47 (3.5, 5.8)	3.74 ± 0.26 (2.5, 4.3)	1.19 ± 0.23 (0.68, 2.2)
TN (mg/L)	61	37.4 ± 5.3 (25.1, 44.8)	31.46 ± 7.3 (18.6, 42.1)	15.1 ± 0.84 (13, 17.6)

Note: Influent, primary effluent and secondary effluent. Mean ± standard error (Min, Max).

3.2. Comparison of total phosphorus removal and coagulant dose

In the Seoul Nanji WWTP, a pilot plant pretest was conducted at 140 m^3/d from September 23 to September 25, 2012. Aeration operation conditions were 3.22 ± 2.4 mg/L DO, 6.8 ± 0.21 pH, and 23.2 ± 0.1 °C. To compare the coagulant dosing characteristics of the control unit and the CAST unit under the same coagulation/flocculation conditions for chemical TP removal, the treated TP concentration was continuously monitored during the practice run for 3 days.

When treating wastewater exposed to rapid and strong quality changes, according to the principle of adsorption coagulation with charge neutralization, the required coagulant dose is markedly dependent on the content of negative charge carriers (low and high molecular organic acids, mineral and organic solid matter) in the raw wastewater. To determine this negative charge concentration, the raw wastewater must be titrated with cationic polyelectrolytes, or positively charged iron, or aluminum hydroxo complexes. Streaming current (SC) measurements and cationic demand (CD) determination from titration using positively charged chemicals are shown in Fig. 4. When measuring streaming current (SC), the cationic demand (CD) can be determined directly from the instrument. Fig. 4 shows that the activated sludge effluent has a streaming current (SC) of −487.69 ± 10.29 mV in the pH range 6.8–7.2 and a cationic charge demand of 1.28 ± 0.371 mL.

As shown in Fig. 4, the CAST unit is capable of computing the coagulant dose more quickly and more accurately than any manual titration. The dose is automatically determined and transmitted online from the CAST unit to the dosing pumps. From the results, the streaming current (SC) shows a relatively good correlation with the cationic demand (CD). The concentration of total phosphorus in the influent (activated-sludge effluent) was 0.5–1.75 (0.97 ± 0.28) mg/L. The TP treated effluent concentrations were 0.11–0.43 (0.27 ± 0.09) mg/L in the control unit with a total mass constant feed of 15 mg/L and 0.15–0.27 (0.20 ± 0.04) mg/L in the CAST unit, and a coagulant dose total mass of 9.34–27.9 (12.9 ± 3.4) mg/L depending on the wastewater quality (Fig. 5 and Tables 3 and 4).

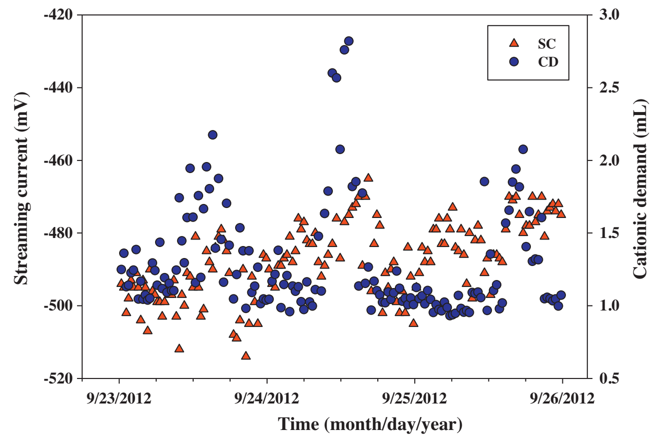


Fig. 4. Variation of streaming current (SC) and cationic demand (CD) on the change of activated sludge effluent by CAST units from September 23 to September 25.

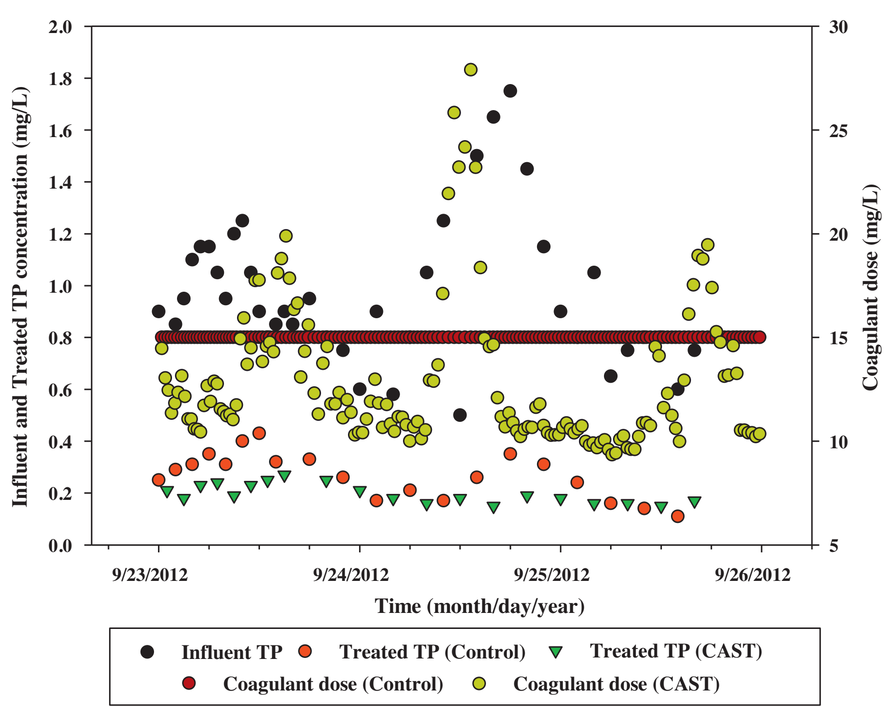


Fig. 5. Variation of influent, treated TP, and coagulation dose in control and CAST units from September 23 to September 25.

Table 3
Comparison of Influent and treated TP concentrations of the control and CAST units.

Date	Sample		Control		CAST	
	N	Influent TP (mg/L)	*N*	Treated TP (mg/L)	*N*	Treated TP (mg/L)
23/9/2012	19	0.97 ± 0.15 (0.75, 1.25)	10	0.33 ± 0.06 (0.25, 0.43)	10	0.22 ± 0.03 (0.18, 0.27)
24/9/2012	12	1.07 ± 0.41 (0.5, 1.75)	6	0.25 ± 0.07 (0.17, 0.35)	6	0.18 ± 0.02 (0.15, 0.21)
25/9/2012	9	0.79 ± 0.13 (0.6, 1.05)	5	0.16 ± 0.06 (0.11, 0.24)	5	0.16 ± 0.01 (0.15, 0.18)
Total	40	0.96 ± 0.28 (0.50, 1.75)	21	0.27 ± 0.09 (0.11, 0.43)	21	0.20 ± 0.04 (0.15, 0.27)

Table 4
Comparison of TP removal and coagulation dose in the control and CAST units.

Date	Control		CAST	
	TP removal (%)	Coagulant dose (mg/L)	TP removal (%)	Coagulation dose (mg/L)
23/9/2012	66 ± 5.7 (52, 72)	15	75.8 ± 5.7 (68.8, 84.2)	13.3 ± 2.4 (10.3, 19.9)
24/9/2012	79 ± 5.0 (73, 86.4)	15	76.8 ± 12.1 (64, 91)	13.3 ± 4.6 (10.0, 27.9)
25/9/2012	77 ± 5.9 (77. 82.5)	15	80.4 ± 2.9 (77.3, 84.8)	11.9 ± 2.8 (9.34, 19.5)
Total	72 ± 8.4 (52, 86.4)	15	77 ± 7.6 (64, 91)	12.9 ± 3.4 (9.34, 27.9)

The results presented in Table 4 show that the CAST unit's coagulation–precipitation process performed better with respect to TP removal (77 ± 7.6%) as compared to the control unit (72 ± 8.4%). The CAST unit showed a 14% reduction in the coagulant dose as well as a 5% increase in TP removal efficiency. By changing the influent of total phosphorus from 0.5 mg/L to 2 mg/L for one day, the CAST pilot system controlled the coagulant dosing and was able to meet the plant's current total phosphorous discharge level requirement, <0.5 mg/L, as shown in Table 3 and Fig. 5. In contrast, the control unit met the discharge limit by a constant feeding of the coagulant dose. This control unit practice ignores variations in influent water sample concentrations, which may lead to chemical over- or under-feeding and may also encourage additional chemical dosing, as shown in Fig. 5 and Table 4. However, lab work is time-consuming and may take several days for collection of essential quantitative data, preservation, analysis and reporting.

Currently most WWTP operators determine coagulant dose by the stoichiometric ratio of metal:phosphorus (Me:P) in the precipitant depending on the phosphate concentration in the liquid, chemical dose, age of the hydroxyl complex, mixing, and many other factors [20,21]. TP removal efficiency depends on the chemical dose, pH, and temperature. To complicate matters, the metal hydroxyl precipitant and reactions also depend on mixing intensity, age of the precipitant, and other factors. Therefore, the required dose must often be determined based on practical experience for a given application.

3.3. Optimal operation factor for total phosphorus discharge level

The results of 33 days of continuous monitoring of influent and effluent TP concentrations and coagulant doses are presented in Table 5 and Fig. 6(a) and (b). The operation factor in the CAST unit plays a substantial role in determining the optimized operation conditions for the target limit as well as the effective chemical dosing strategy. For CAST operation Factor 13 for 23 days, TP was reduced from 1.9 ± 2.1 mg/L to 0.21 ± 0.1 mg/L (87 ± 8.4%) with the continuous addition of coagulant doses in a range from 8.6 to 18 mg/L (average 12.6 ± 1.86 mg/L) and the treated TP concentration remained close to <0.3 mg/L (Fig. 6(a)). Meanwhile, for operation Factor 10 for 10 days, TP was reduced from 2.3 ± 1.3 mg/L to 0.43 ± 0.04 mg/L (81 ± 4%) with the continuous addition of coagulant in a range from 8.2 to 17.6 mg/L (average 12.2 ± 2.38 mg/L), and the treated TP concentration remained close to <0.5 mg/L (Fig. 6(b)). For target concentrations below 0.5 mg/L, an operation Factor from 10 to 13 is sufficient. For phosphorus concentrations below 0.3 mg/L, Factor 13 would be best. After November 28, the influent TP concentration increased continuously and the treated TP concentration was close to the target limit under the Factor 10, as shown in Fig. 6(b).

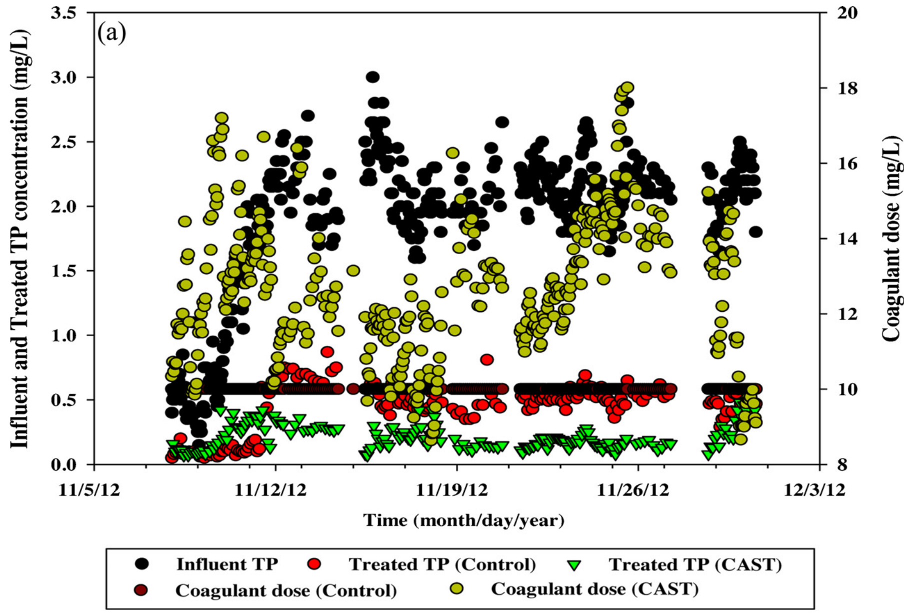
As shown in Fig. 6(a) and (b), the decrease in the coagulant dose from an initial 15 mg/L (Section 3.2) to 10 mg/L resulted in much less stable effluent phosphorus, which averaged 0.48 ± 0.2 mg/L in the control unit. The constant 10 mg/L feed of coagulant controlled by the site's operator was not enough to meet the site requirement level for a TP concentration below 0.5 mg/L, nor to not satisfy the discharge limit in 162 out of 264 samples.

A comparison of TP removal in the control and CAST systems is shown as interval plots using a 95% confidence level in Fig. 6(a) and (b). The interval plots display the mean values with error bars as well as the confidence intervals. Fig. 7(a) and (b) shows that the spread of data obtained for the control system is larger than that for the CAST system, indicating that the control system has greater variability in TP removal than the CAST system. As climate change becomes an ever more serious global issue, more frequent intensive rainfall events will routinely affect the quality of the wastewater influent to WWTPs, and increase the flow of the influent in some cases [22,23]. As such, the jar test (control system)

Table 5
Comparison of influent and treated TP concentrations in the control and CAST units.

Operation	Activated-sludge effluent		Control unit		CAST unit	
	N	Influent TP (mg/L)	*N*	Treated TP (mg/L)	*N*	Treated TP (mg/L)
Factor = 13[a]	358	1.9 ± 2.1 (0.15, 3.0)	189	0.43 ± 0.2 (0.05, 0.87)	189	0.21 ± 0.1 (0.07, 0.42)
Factor = 10[b]	166	2.3 ± 1.3 (1.55, 2.95)	83	0.59 ± 0.1 (0.32, 0.85)	83	0.43 ± 0.04 (0.31, 0.49)
Total	524	2.0 ± 1.3 (0.15, 3.0)	264	0.48 ± 0.2 (0.05, 0.87)	264	0.27 ± 2.1 (0.07, 0.49)

[a] Variation of influent, treated TP, and coagulation dose in control and CAST units for 23 days (11/8/2012–11/30/2012).
[b] Variation of influent, treated TP, and coagulation dose in control and CAST units for 10 days (1/12/2012–12/12/2012).



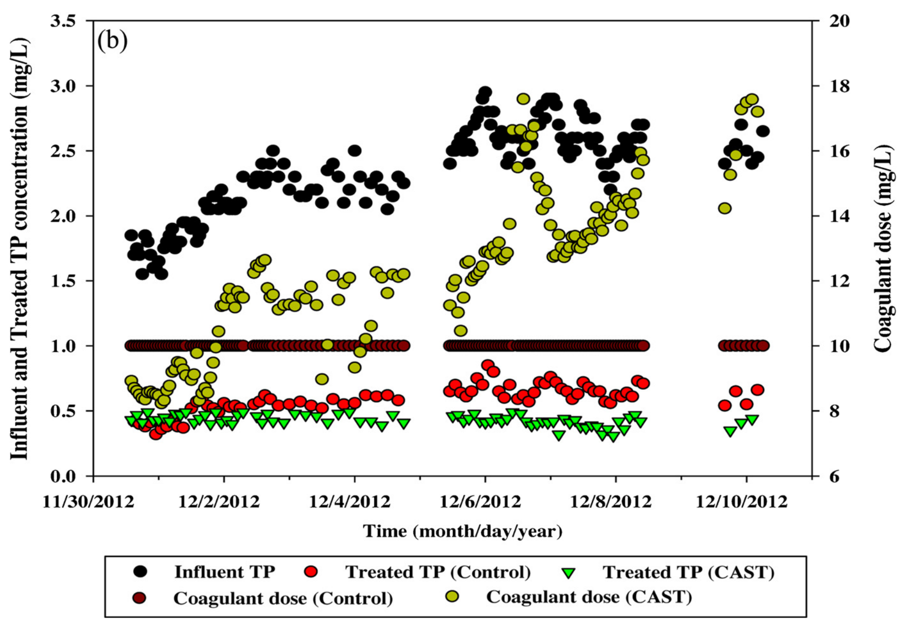


Fig. 6. Variation of influent and treated TP concentration by controlling the CAST Factor: (a) CAST operation Factor 13 and constant 10 mg/L feed of coagulant by control system for 23 days and (b) CAST operation Factor 10 and constant 10 mg/L feed of coagulant by control system for 10 days.

is not appropriate for municipal wastewater with highly fluctuating wastewater quality, as shown in Fig. 7(a) and (b).

The TP reduction performances of the coagulation–sedimentation system by coagulant dose type (control and CAST systems) and by initial coagulant dose (constant 10 mg/L feed of PAHCS dosage by control and real time dosing with controlling operation factor = 10) were compared using paired *t*-tests at the 95% confidence level. The paired *t*-test results are shown in Table 6. From the data presented in Table 6 for the paired *t*-test it is possible to see that there is a significant difference ($p < 0.001$) between the control and CAST systems at the 95% confidence level, indicating that the CAST system was much more effective than the jar test (control) system currently in use at the plant.

From the data presented in Table 6 for the two-sample *t*-test it is also possible to see that there is a significant difference ($p < 0.001$) between the TP reduction performance of the CAST system by controlling each operating factor at the 95% confidence level. This difference in TP removal between factor = 13 and factor = 10 might be caused by several reasons. Flocculation is the process of bringing together these microfloc particles to form large agglomerations by physically mixing them or through the binding action of flocculants (such as long-chain polymers) [24]. The coagulation conditions for factor = 10 are less optimal than those for factor = 13. Thus, smaller colloidal and soluble ion species may be present, which will affect TP reduction. However, factor = 13 shows only around 6.96% more efficiency in TP removal than factor = 10.

To meet the target standard a stable operating condition is preferable to Factor 13. Furthermore, the average difference in the coagulant dose addition between Factor 10 and Factor 13 was not

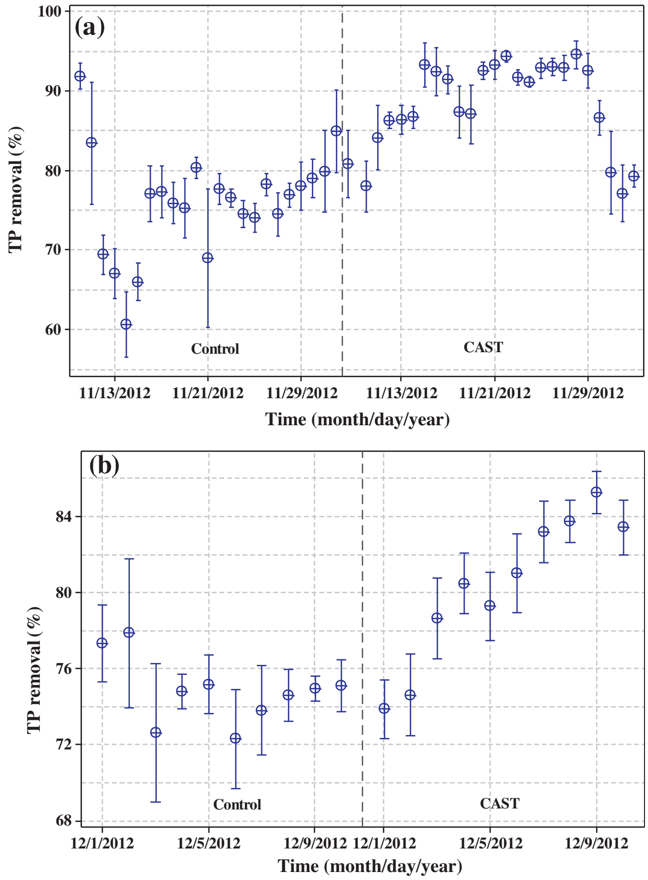


Fig. 7. TP removal (%) for the control (left panel) and CAST (right panel) systems plotted with 95% confidence intervals for data from Table 6: (a) CAST operation with factor = 13 over 23 days and (b) CAST operation with factor = 10 over 10 days.

Table 6
Values of the paired *t*-test and two-sample *t*-test for TP removal under two different conditions.

Items	Comparison of two samples or conditions					
	Control		CAST		Statistical analyses	
	N	Mean ± SD	*N*	Mean ± SD	*t*-Value	*p*-Value
Coagulant dose type[a]	264	76.8 ± 6	264	85 ± 8	−10.23	0.0001
Initial coagulant dose[b]	83	74.6 ± 8	83	81 ± 4	−10.64	0.0001
Items	Comparison of two samples or conditions					
	Factor = 13		Factor = 10		Statistical analyses	
	N	Mean ± SD	*N*	Mean ± SD	*t*-Value	*p*-Value
CAST operation factor[c]	189	87 ± 8.4	83	81 ± 4	11.12	0.0001

[a] Comparison of control and CAST systems using the paired *t*-test for 23 days (11/8/2012 to 11/30/2012).
[b] Injection condition of initial coagulant by control and CAST system with the paired *t*-test for 10 days (1/12/2012 to 12/12/2012).
[c] Comparison of CAST operation factor with the two-sample *t*-test for 21 days (11/8/2012 to 11/30/2012).

significant. This finding may have important implications for controlling operation conditions in the future, if the city of Seoul needs to achieve stable effluent TP concentrations below 0.5 mg/L. The control unit frequently exceeded the discharge limit level of 0.5 mg/L of TP, with a maximum TP concentration of 0.87 mg/L. The WWTP phosphorus control system with the CAST unit proved that it performs well in providing the coagulant dose necessary, in response to the wastewater quality in real-time, to meet the effluent TP target value. By avoiding overdosing it helps to curb the amount of treatment sledges, and consequently reduces landfill costs.

4. Conclusion

In this study, a new coagulant dose control system using an online CAST was tested for its ability to manage total phosphorus removal from municipal wastewater.

In pretest comparisons, the average coagulant dose using the CAST unit was 12.9 ± 3.4 mg/L compared to the average coagulant dose of 15 mg/L by the control unit. Over the three month study period, this equates to a reduction in the average coagulant dose of 2.1 mg/L (14%) and a 5% increase in the average TP removal by the CAST unit, while maintaining an effluent TP concentration lower than the 0.5 mg/L target limit.

For optimal operation conditions, we conclude that the CAST operation Factor range that best meets the TP discharge limit is between 10 and 13, resulting in a 87 ± 8.4% TP reduction (influent: 1.9 ± 2.1 mg/L, effluent: 0.21 ± 0.1 mg/L) in Factor 13, and a 81 ± 4% TP reduction (influent: 2.3 ± 1.3 mg/L, effluent: 0.43 ± 0.04 mg/L) in Factor 10. Field evaluations verified that the TP discharge level could be consistently reduced to less than 0.5 mg/L by Factor 13 rather than Factor 10. Although the influent and effluent TP varied over the monitoring period, Factor 13 was observed to consistently meet the target limit. However, for the control unit dose determinations by jar tests, the coagulant dosage of 10 mg/L was not able to satisfy the discharge limit for 162 out of 264 samples.

A jar test (control unit) has traditionally been used to determine the chemical coagulation conditions in WWTPs. However, due to this method's frequent and intermittent measurements, and the time-consuming nature of the tests, achieving optimal coagulation conditions using the jar test is not appropriate for rapidly changing water-quality conditions.

In this study, the online CAST system successfully demonstrated its capability in gathering timely, accurate and reliable WWTP data to ensure that enhanced effluent limits can be met, and that the treatment process is optimized. Future research on the CAST system should address its benefits regarding sludge production, and conduct tests over a longer study time frame of one to two years to make possible a full cost-benefit analysis that includes an understanding of the system's maintenance requirements.

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