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Cost analysis and effects of various coagulants used for sludge treatment at the full-scale wastewater treatment plant

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ABSTRACT

The economic potential of poly-aluminum chloride (PAC) at full-scale sludge treatment plant and its impact on sludge production was explored in this study. The effect of recycling water on major parameters of wastewater treatment plant (WWTP) such as chemical oxygen demand (COD), suspended solids (SS), total nitrogen (TN) and total phosphorus (TP) was investigated. Comparative cost-analysis for powdered polymer coagulant (PPC), liquid polymer coagulant (LPC) and PAC was made for the period of 2016–2019 while the impact of recycling water from the sludge treatment section on to the effluent characteristics was conducted for six months before and after PAC application. Coagulants cost per ton of sludge treatment was dropped by 15% without increasing sludge production after PAC application in combining with PPC instead of LPC. TN removal efficiency of the WWTP was about 6% while TP 1% that can be attributed to the mixing of PAC loaded recycling water from sludge treatment section with the influent. COD and SS removal were slightly dropped throughout the period of 2016–2019. After PAC application, mixing of recycling water from the sludge treatment section with the influent significantly decreased the fluctuation in TP concentration of the effluent. Therefore, PAC can be an economical and environmentally sustainable option for sludge treatment at full-scale WWTP.

Keywords: Coagulants; Cost analysis, Recycling water; Sewage sludge treatment

1. Introduction

Economic and environmental sustainability are getting more attention in the wastewater management system [1]. The conventional activated sludge process (CASP) has been used for wastewater treatment to minimize water streams contamination, however, it has a considerable environmental and economic impacts associated with the usage of chemicals, energy requirements, sludge production and gas emissions [2,3]. Organic pollutants are removed effectively through the metabolism of microorganisms in CASP but it generates a large amount of sludge that needs further treatment. Although various sludge treatment techniques such as incineration, landfilling and ocean pumping are applied around the globe there are concerns regarding secondary pollution due to the strict environmental regulations nowadays [4]. The cost of sewage sludge treatment and its disposal can be as high as 25%–65% of the total operational cost of a wastewater treatment system [4,5]. Nutrients removal from the effluent is another main problem encountered in CASP. Nutrients contamination in water streams caused by the accumulation of nitrogen and phosphorus compounds discharged from the wastewater treatment plants (WWTPs) has become one of the major environmental challenges [6]. Moreover, water generated by sludge treatment system including digestor, concentrator

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and dehydrator were loaded with total nitrogen (TN), total phosphorus (TP) and suspended solids (SS) that ultimately impact the primary settling at WWTP when mixed with the influent [7]. In the 1990s, recycling water from the sludge treatment section loaded with TN and TP was not recognized as an important part of the sludge treatment system. Although effluent generated in the sludge treatment section is only 1% to 3% of the inflow it can increase 13% to 46% of influent TP load due to high concentration of organic matter that is difficult to decompose through biological treatment. Later on, it was considered a significant part of the sludge treatment system because of its impact on the operation of the biological reactor [8,9].

Numerous techniques including chemical, biological and membrane technologies were applied to eliminate nutrients from wastewater effluent [10–14]. According to the treatment technologies used at public sewage treatment facilities, sequence batch reactor (SBR) series treatment technology was found to be advantageous in TN removal while A_2O series treatment technology was more attractive for TP removal [15]. Although nutrients removal was improved in the aforementioned systems their operational cost was also increased. A big challenge in wastewater management is no return on investment because of which local authorities did not show a keen interest in this sector [16]. Regardless of newly existing technologies, knowledge and expertise to advance the alternatives for water sources management using economical and environmentally sustainable options, the implementation of those technologies still below the mark [17,18]. Some studies suggested that the development of a cost-effective alternative for the management of wastewater systems is an administration issue rather than technology one [19]. Lack of economic viability of those alternative solutions creates trouble in their practical implementation as reasonable and feasible options [20]. In terms of economy and environment sustainability for the management of WWTP, the consumption of chemicals is becoming an interesting area of research [21]. Generally, polymer chemicals are used in the sludge treatment section where coagulants are an important one. They are ionically charged low molecular weight compounds that neutralize the charge of suspended solids to support the aggregation of suspended particles. The selection of the best coagulant depends upon the design, operation of the treatment plant, type of suspended solids and characteristics of the effluent that can impact both economics and regulatory compliance [22]. It is important to find the best coagulants combination for sludge treatment and their impacts on WWTP overall. Previously various applications in wastewater treatment systems were explored as mentioned in a review article [5]. However, no study was found for Taeyoung external carbon addition biological nutrient removal (TEC-BNR) system with a microbubble flotation process to the best of our knowledge. TEC-BNR is a complex biological process and its treatment efficiency can be optimized economically by selecting the best coagulants combination for the sludge treatment and their impact on water quality parameters. The aims of this study include, (1) to investigate and compare the economics of various coagulants, (2) to explore the impact of coagulants on sludge production, (3) to study the effects of recycling water on the effluent characteristics [chemical oxygen demand (COD), SS, TN, and TP], and to draw a comparison before and after poly-aluminum chloride (PAC) application.

2. Materials and methods

2.1. Materials

Commercial polymers powdered polymer coagulant (PPC) and liquid polymer coagulant (LPC) with trade names of C-4441VHM and C-840TBD were procured from SNF chemicals, South Korea. PAC with 10% purity was purchased from NID Chemical while all lab-grade chemicals were used for the analytical purpose procured from Merck, South Korea. PAC effectively used for various water treatment applications due to low consumption, no additional chemical required for neutralization, fast in reaction and does not increases the sludge production as reported in a study [23]. The characteristics of the PAC are presented in Table 1.

2.2. Wastewater treatment plant

This study was conducted through experimental and operational data of a full-scale WWTP from January 2016 to September 2019, located in Gimcheon, Republic of Korea. The capacity of the plant was 80,000 m^3/d and the influent contained both domestic and industrial wastewater with a population equivalent of 172,728. After a secondary clarifier, all the effluents were combined and drained out. Similarly, all the sludge was combined and sent to the sludge treatment section. The schematic diagram of TEC-BNR with a microbubble flotation process for the domestic and industrial wastewater treatment is shown in Fig. 1. TEC-BNR is a post-denitrification system that is consisted of anaerobic, aerobic, anoxic and a clarifier tank. The post-denitrification requires an external carbon source where organic

Table 1
Characteristics of PAC, PPC and LPC

PAC	
Specific weight @20°C	1.19 mg/L
Contents of Al_2O_3	10%–12%
Appearance	Yellow color liquid
Basicity	35%
Sulfate ion	3.5%
PPC	
Trade name	C-4441VHM
Total solids	90%–100%
1% solution viscosity	3,000–6,000 cps
Ionicity	Medium
LPC	
Trade name	C-840TBD
Non-volatile solids	48.5%–53.5%
1% solution viscosity	300–500 cps
Ionicity	High
cps; centipoise	

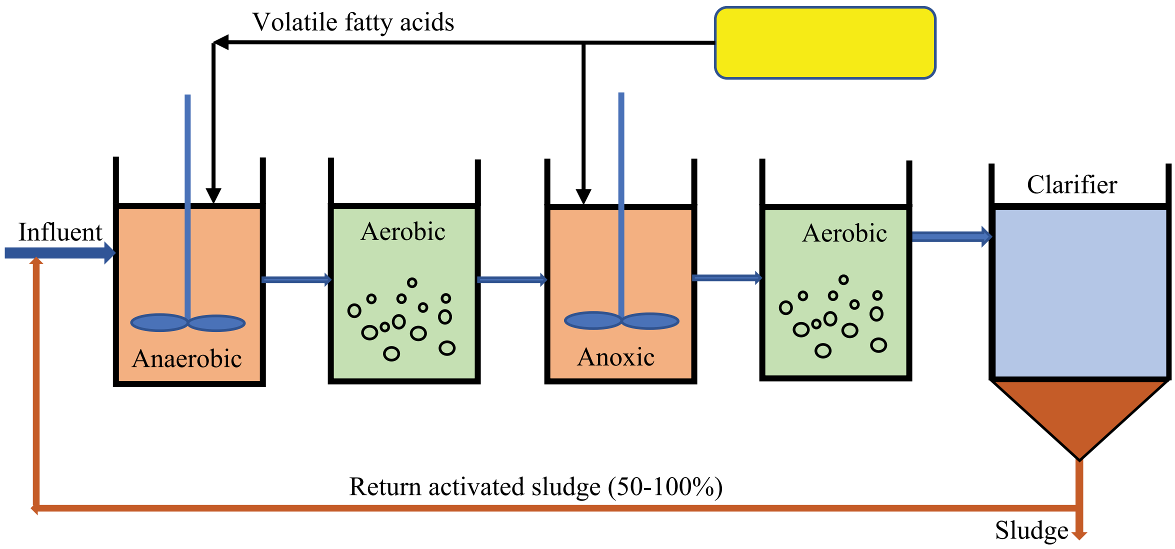

Fig. 1. Taeyoung external carbon addition biological nutrient removal (TEC-BNR) wastewater system.

acid produced through hydrolysis and hydrocarbon-based compounds undergoes acid fermentation for the removal of nitrogen and phosphorus without any internal circulation. The anaerobic process is a plug flow system consists of three compartments where mixer provides satisfactory mixing and also maintain a specific velocity to avoid the settling of solids [24]. This process is typically used for the treatment of wastewater with a high concentration of biodegradable organic matter. Unlike the aerobic process, anaerobic and anoxic processes do not require oxygen that is an energy-intensive process. In anoxic tank during the denitrification process, nitrogen is converted to nitrate first. Then organisms in the absence of free oxygen use the nitrate as an electron acceptor and release nitrogen in the form of gas [25].

2.3. Sludge treatment system

The sludge treatment process includes sludge thickening, dewatering and drying followed by compost manufacturing facility as shown in Fig. 2. The sludge line is comprised of three core treatment stages, where diverse associated processes are conducted, including, concentration, dewatering and drying process. In the concentration process, sludge volume is reduced by eliminating water to increase the concentration of solids [26]. The biological process oxidizes organic matters through microbiological activity by supplying oxygen in open digesters that decrease the final mass of the produced sludge which is helpful for the adaption at later stages. Afterward, dewatering a mechanical operation utilized for the reduction of water contents in the sludge and ultimately decrease the sludge volume [27]. The major targets in sludge treatment include dry matter content increment by 3% to 40%, reduction in transport costs by decreasing sludge volume, improvement in the handling and transportation, evade odors, calorific value increased by lessening the humidity [28]. The water contents removal from sludge is a basic unit operation for the reduction of the sludge volume by thickening and dewatering prior to further treatment [29]. The blending of primary and biological sludges provides easy dewatering due to the intrinsic properties of the sludge. The concentration of the sludge influences the coagulant dosage because at higher concentrations it is hard to mix the coagulant even at low concentration. Generally, sludge is conditioned before thickening and dewatering to enhance the treatability of the sludge by conditioning chemicals such as minerals and organic chemicals. Mainly organic chemicals used in sludge dewatering where destabilized particles are agglomerated in aggregates known as flocs due to their salient features including, high molecular weights and varied ionic charge to fix the destabilized particles. Resultantly, particle size will increase in the aqueous phase and induces the easy removal of water in the dewatering step [24]. The coagulants are characterized based on their carrying charge and density, molecular weight and structure along with the type of the monomer. The type of charge is selected according to the charge type of the particle. Cationic coagulant used to catch organic particles while anionic can attach the mineral particles that can be checked through laboratory analysis. The charge density indicates the quantity of the charge required to attain the best coagulation at a low dosage of coagulant and it depends upon the type of the sludge. For example, charge density in municipal sludge is a function of organic matter present in the sludge [27,28]. On the other hand, in the case of industrial sludge charge density varies as sludge characteristics changes. The selection of the molecular weight of a coagulant depends on the type of equipment used for dewatering. The molecular structure is chosen based on the required performance of dewatering, linear, branched or cross-linked structure polymers [26]. The recycling water from the sludge treatment section loaded with nitrogen, phosphorous and suspended solids which disturb the efficiency of the primary settling systems [30]. The inflow to the sludge treatment section is intermittent that can be a detrimental operating factor of the system running on the basis of average inflow water quality, therefore, recycling water is an important factor to achieve a stable operation of the WWTP [31].

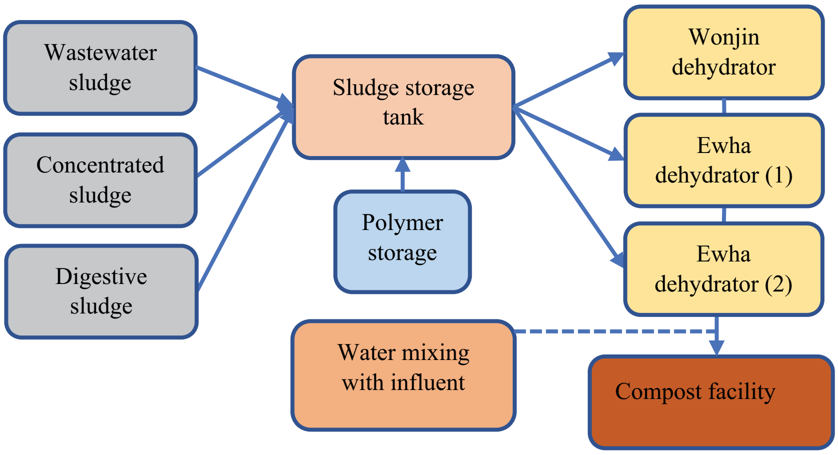

Fig. 2. Schematic diagram of the sludge treatment system at the TEC-BNR process.

2.4. Influent and effluent characteristics

The main characteristics of influent and effluent including TN, TP, COD and SS for domestic and industrial wastewater are presented in Tables 2 and 3, respectively. The annual average value of effluent was presented in Table 4. Domestic and Industrial influents are treated separately while effluent was mixed after secondary clarifier and sludge were also combined before feeding to the sludge treatment section. Hourly analysis data was considered for a better understanding of variation in parameters and to discuss their impact on the effluent characteristics.

2.5. Analytical methods

The physicochemical parameters of the influent and effluent such as TN, TP, COD, and SS were measured according to the Standard Methods for the Examination of Water and Wastewater. A standard method of analysis ES-04363.1 was used to measure TN in the water sample. All the nitrogen-based compounds were decomposed at about 120°C using alkaline potassium persulfate. A standard method of analysis ES-04362.1 was employed to analyze TP in the form of organic compounds. All phosphorous compounds PO_4^{3-} converted to phosphate by oxidative decomposition.

Table 2
Domestic influent characteristics

Parameters	Units	Annual domestic wastewater characteristics											
		2016			2017			2018			2019		
		X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}
COD	mg/L	104	160	132	109	152	127	105	167	133	86	127	101
SS	mg/L	139	237	184	138	204	176	149	220	150.7	118	190	146
TN	mg/L	32.27	43.47	37.92	33.59	47.63	42.99	38.16	42.82	39.65	37.66	47.67	41.57
TP	mg/L	3.59	5.14	4.25	3.58	5.29	4.61	3.78	5.08	4.45	3.15	4.32	3.71

X_{min}, X_{max}, X_{mean}: minimum, maximum and mean values

Table 3
Industrial influent characteristics

Parameters	Units	Annual industrial wastewater characteristics											
		2016			2017			2018			2019		
		X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}
COD	mg/L	89	138	113	78.3	1133	105	93	148	115	78	109	92
SS	mg/L	122	185	147	104	181	143	127	209	149	101	153	120
TN	mg/L	28.11	35.78	31.47	26.10	44.38	36.04	29.56	35.47	32.60	27.49	34.29	30.36
TP	mg/L	2.77	3.98	3.27	3.27	4.54	3.92	3.42	4.97	4.06	2.79	3.89	3.44

X_{min}, X_{max}, X_{mean}: minimum, maximum and mean values

Table 4
Characteristics of combined effluent

Parameters	Units	Annual effluent characteristics											
		2016			2017			2018			2019		
		X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}	X_{min}	X_{max}	X_{mean}
COD	mg/L	8.60	12.70	10.40	9.70	12.50	11.30	10.0	12.7	11.2	10.5	12.70	11.60
SS	mg/L	3.40	4.90	4.10	3.60	4.40	3.90	4.0	5.20	4.60	5.0	6.0	5.6
TN	mg/L	8.69	11.51	10.34	8.49	11.53	10.03	7.94	12.29	9.20	7.34	10.70	8.72
TP	mg/L	0.076	0.123	0.098	0.055	0.120	0.084	0.062	0.105	0.089	0.054	0.129	0.089

X_{min}, X_{max}, X_{mean}: minimum, maximum and mean values

Then reducing phosphorous molybdate ammonium produces molybdate after reaction with ammonium to ascorbic acid. The absorbance of molybdate at 880 nm provides the quantity of TP in the sample. Duplicate samples were prepared to confirm the analytical results. COD measurement in the water sample was conducted using potassium permanganate standard method of analysis ES-04315.1. A measured volume of water sample was taken into a flask and added a specific amount of sulfuric acid and potassium permanganate. After shaking, the flask was placed in a boiling water bath and heated for 30 min and titration was conducted. The same procedure was done in parallel with distilled water and COD potassium permanganate was calculated. A standard method ES-04303 was used to measure the SS in the effluent and standard jar tests were conducted to optimize the dosage of PAC at lab-scale. A lab-scale jar-test was used for determining the optimum dosing rate of PAC for dewatering of sludge in terms of economic feasibility and its impact on TP concentration in the effluent. The experiments were conducted at various concentrations, dosing rates and pH values for evaluating the effectiveness of PAC in treating combined domestic and industrial wastewater. After finding an optimum dose in the lab-scale study it was implemented at the full-scale plant afterward its economic and environmental sustainability was monitored continuously.

2.6. Economic feasibility of PAC

In this study, an economic analysis of PAC coagulant was conducted when used in combination with PPC as a replacement of LPC for a full-scale sewage sludge treatment. In parallel, the impact of PAC application on water quality parameters especially TP concentration was focused during lab-scale studies. First of all, lab-scale experiments were conducted using different concentrations and dosages of PAC to reach an optimum result and continuously monitored. After lab-scale studies, calculations were made using MS Excel as a computational simulator to make a full-scale extrapolation in terms of economy and TP concentration of effluent. Then hourly data of full-scale plant was monitored to observe the aforementioned impacts of PAC as well as its additional effects on water quality parameters such as TN, COD and SS. The cost of PAC consumption was evaluated and compared with the cost of previously used LPC and then an assessment was made by checking the monthly cost of PAC and PPC with LPC and PPC combination to show the economic feasibility. Sludge production was also monitored during this period because if it increases that means the additional cost is required for handling and treating produced sludge. Moreover, the impact of PAC on water quality parameters, including, TN, TP, COD and SS was observed to check the suitability of selected coagulants at full-scale sewage treatment plants.

3. Results and discussion

In the following sections, we have presented an economic aspect of WWTP regarding coagulants consumption cost per ton of sludge treatment, sludge production and impacts of recycling water on TN, TP, COD and SS in the effluent along with a comparative study before and after PAC application at a full-scale sewage treatment plant.

3.1. Coagulants consumption cost and sludge production

The average cost per ton of sludge treatment for both commercial coagulants PPC and LPC was calculated yearly. It was noted as 1.68, 1.18, 1.42 and 1.46 US$ for the years of 2016, 2017, 2018 and 2019, respectively as shown in Fig. 3a. Higher cost per ton of sludge treatment was found in the year of 2016 because commercial coagulants PPC and LPC were used for sludge treatment. In the mid of February 2017, the LPC coagulant was replaced with PAC after the completing experimental studies in the laboratory. PAC is economical than LPC therefore, a sharp drop in cost was noticed during the 3rd month of the year 2017 probably due to the feeding of PAC that was started in mid-February 2017. Afterward, a slight increase was noticed until the end of the year that might be due to the variation in sludge characteristics associated with influent properties. In the year 2018, a similar trend was indicated without any sharp drop and in the second half of the year, it becomes almost constant. On the other hand, the year 2019 showed an increase in cost during the third and fourth months but later dropped back to the average cost as noted in the year 2018. To compare the economics of coagulants previously used for sludge treatment, we evaluated the monthly cost of PPC (PPCC) and LPC (LPCC) for the years 2016 and 2017 presented in Fig. 3b. The plot of PPCC and PACC during the period of 2018–2019 is shown in Fig. 3c. LPCC was higher than PPCC in the year 2016 but after replacing LPC with

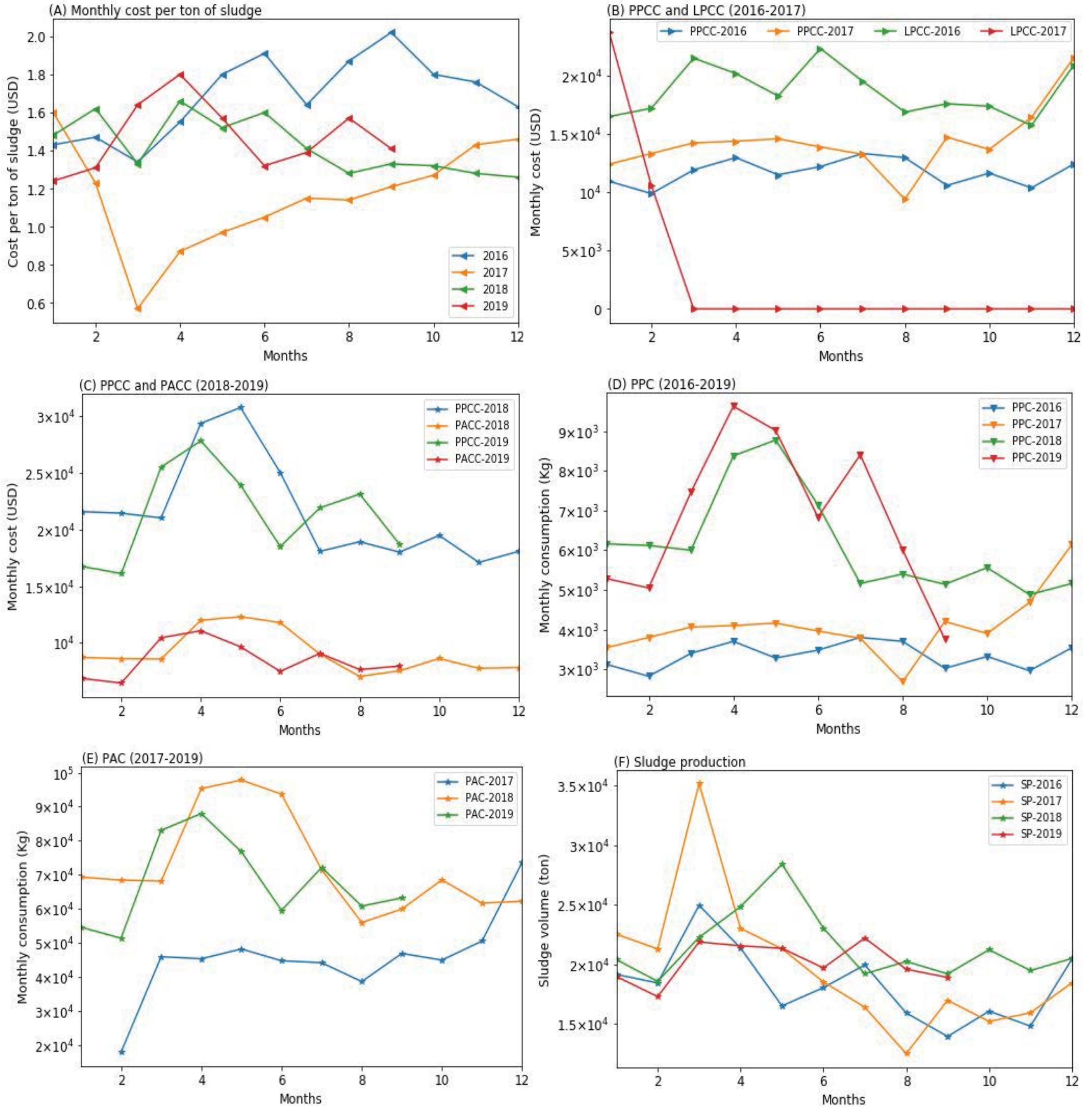

Fig. 3. Change of monthly cost and consumption of coagulants and sludge production.

PAC an increase in PPCC was noted due to an increase in its consumption. The higher consumption of PPC was to attain efficient coagulation before feeding the sludge to the dehydrator. It is evident from this plot that the monthly PPCC increased due to its high consumption as compared to the previous year even PAC was used in combination with PPC for best coagulation. The monthly consumption of PPC and PAC was also noted to check the trend of dosage as shown in Figs. 3d and e. Higher consumption of PPC increased the operational cost of the plant but the overall cost was still less than the cost beard per year by using PPC and LPC due to the low cost of PAC. The trend of PPC and PAC monthly consumption is almost similar to the years of 2018 and 2019 but the dosage of PAC is higher than PPC. During the third, fourth and fifth months, an increase in consumption was noticed that might be due to the change in the characteristics of sludge entered into the sludge treatment section. Therefore, it is clear that PPC and PAC application in sludge treatment can be an economical alternative as compared to commercial coagulants at full-scale sewage sludge treatment plants where the economy is the priority. Monthly sludge production (SP) was also monitored in this study to evaluate the performance of each coagulant as shown in Fig. 3f. It can be seen that the production of sludge was suddenly increased in the third month of 2017. It might happen because previously used LPC was replaced with PAC and there was the possibility of the presence of all the coagulants in the system during that period that might cause an increase in SP. Later on, the SP was decreased as LPC goes out of the system and then its average was within the range as produced during other years with small changes that can occur due to the change in influent characteristics.

3.2. Impact of coagulant on water quality parameters

The newly adopted coagulants resulted in a change in the characteristics of recycling water that ultimately effected the nutrients, COD and SS and their removal. PAC appeared

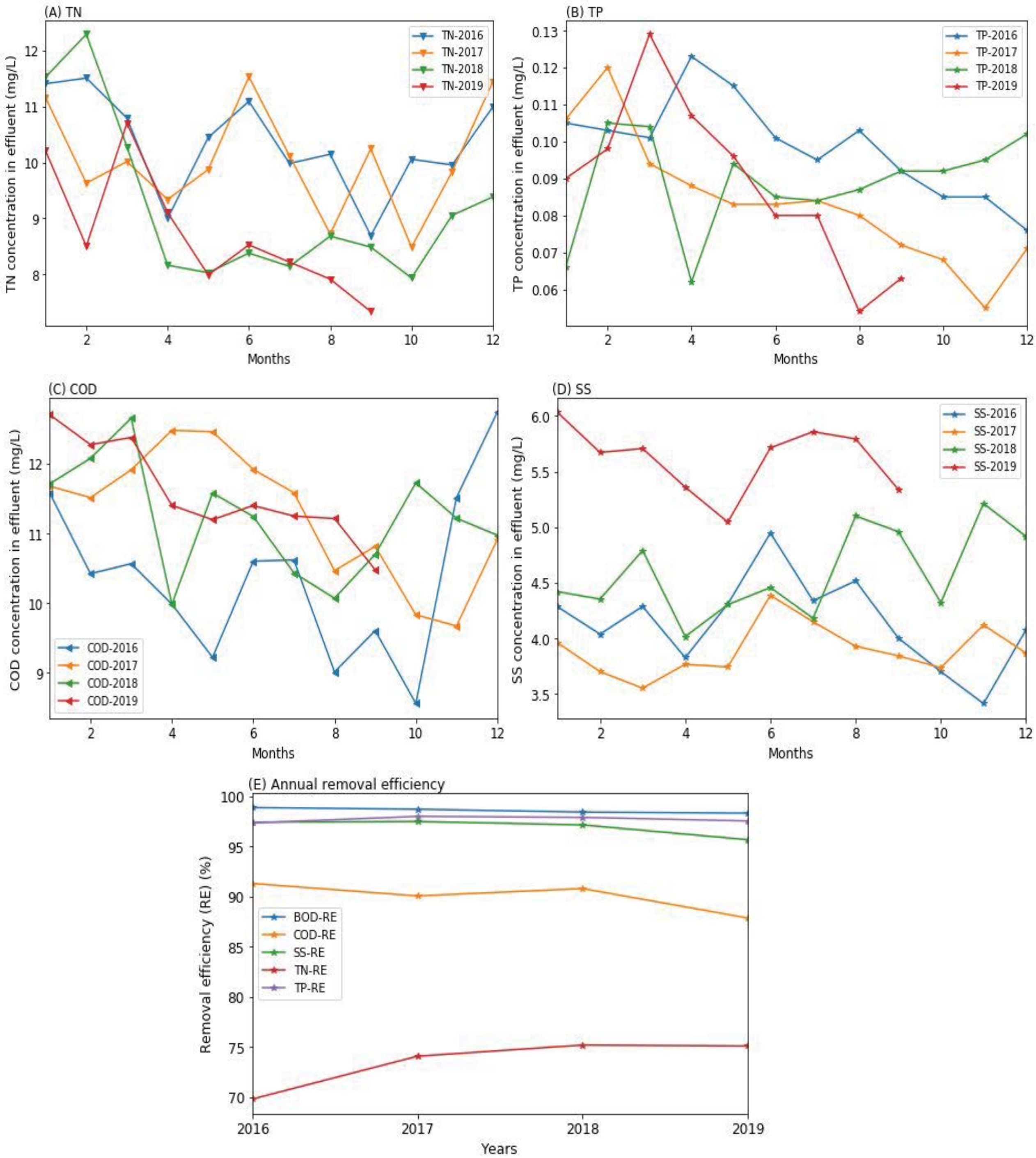

Fig. 4. Monthly changes in effluent characteristics and their annual removal efficiency.

as an economical alternative to the LPC as well as changed the overall performance of WWTP due to the mixing of recycling water. Therefore, it is important to check the impact of the mixing of recycling water on various parameters such as TN, TP, COD, and SS caused due to the replacement of coagulant. The concentration of the aforementioned parameters in the effluent before and after coagulant replacement for the period of the year 2016 to the year 2019 is presented in Fig. 4. The average concentration of TN in the effluent was higher in 2016 as shown in Fig. 4a while dropped afterward during the year 2017 to 2019 resulted due to the replacement of LPC by PAC. A significant improvement in TN removal efficiency from 69% to 75% may be associated with the mixing of recycling water. Its concentration was high in the effluent during the last month of the year 2017 as compared to the year 2016 due to the higher concentration of the influent. TP concentration in the effluent decreased after changing the coagulant while in the last four months of the year 2018, its concentration was slightly on the higher side because its concentration was increased in the influent as shown in Fig. 4b. Overall, its average concentration decreased in the effluent when PAC was used as a coagulant in place of LPC. As shown in Fig. 4c, the effect of PAC showed a negative effect on COD as its concentration increased to some extent in the effluent after changing coagulant during the year 2017 to the year 2019 and a slightly higher concentration of SS was noticed after PAC application as presented in Fig. 4d. Although a small increase in the concentrations of COD and SS were observed the average results were within the standard limits, therefore PAC can be a good and economical option. The removal efficiency of TN, TP, COD and SS was evaluated and plotted yearly basis to highlight

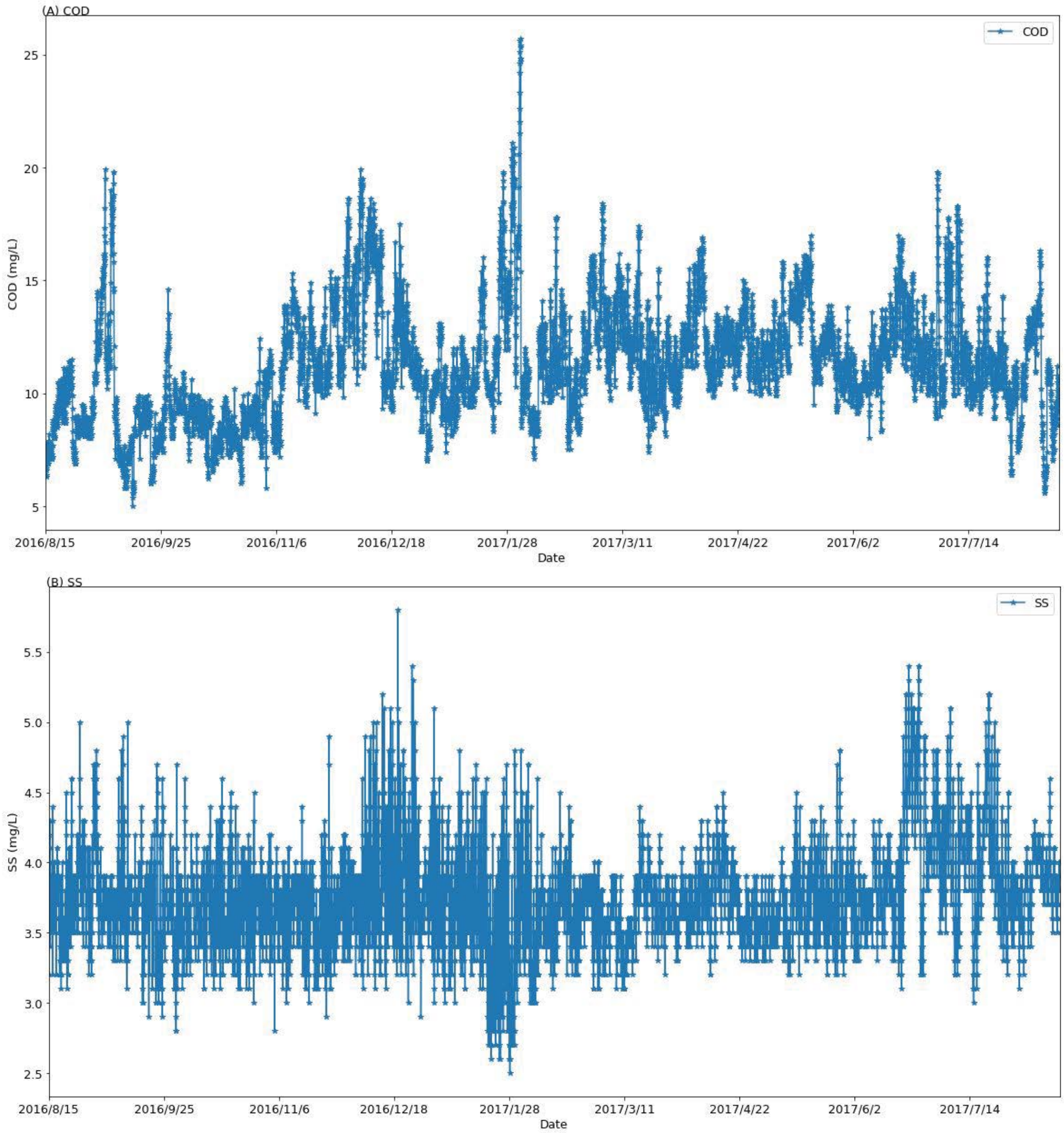

Fig. 5. Hourly COD and SS concentration in the effluent for six months before and after PAC dosage.

the impact of coagulant replacement as shown in Fig. 4e. A significant change in TN removal was observed while TP elimination was slightly improved during the period of the year 2016 to the year 2019. COD removal dropped like 91%, 90%, 90% and 88 % during the years of 2016, 2017, 2018 and 2019, respectively and a small decrease of SS elimination from 97% to 95% was noticed during the same period. This may due to the impact of PAC usage or change in the influent characteristics fed to the wastewater treatment system as recycling water from the sludge treatment section was mixed with influent.

3.3. Comparative study before and after PAC application

It was complicated to show the hourly data of water quality parameters so average monthly values were used in plotting and to present a clear picture of hourly data for a one-year operation was considered. We selected a one-year study, six months before and after PAC dosage to compare the effluent characteristics as presented in Figs. 5 and 6. This study monitored the plant performance for the period of January 2016 to September 2019 but LPC was replaced with PAC on 15 February 2017, hence hourly data of water quality parameters were noted within six months period before and after. The hourly monitoring was started from 15 August 2016 (six months before) till 15 August 2017 (six months after) to compare the effect of PAC on to the concentration of TN, TP, COD, and SS in the effluent. No significant change was noticed in the case of COD and SS concentration in the effluent as shown in Fig. 5, although the average removal efficiency of those parameters was slightly decreased as mentioned in the previous section. TN concentration in the effluent showed a similar trend as COD and SS but its average removal efficiency was improved.

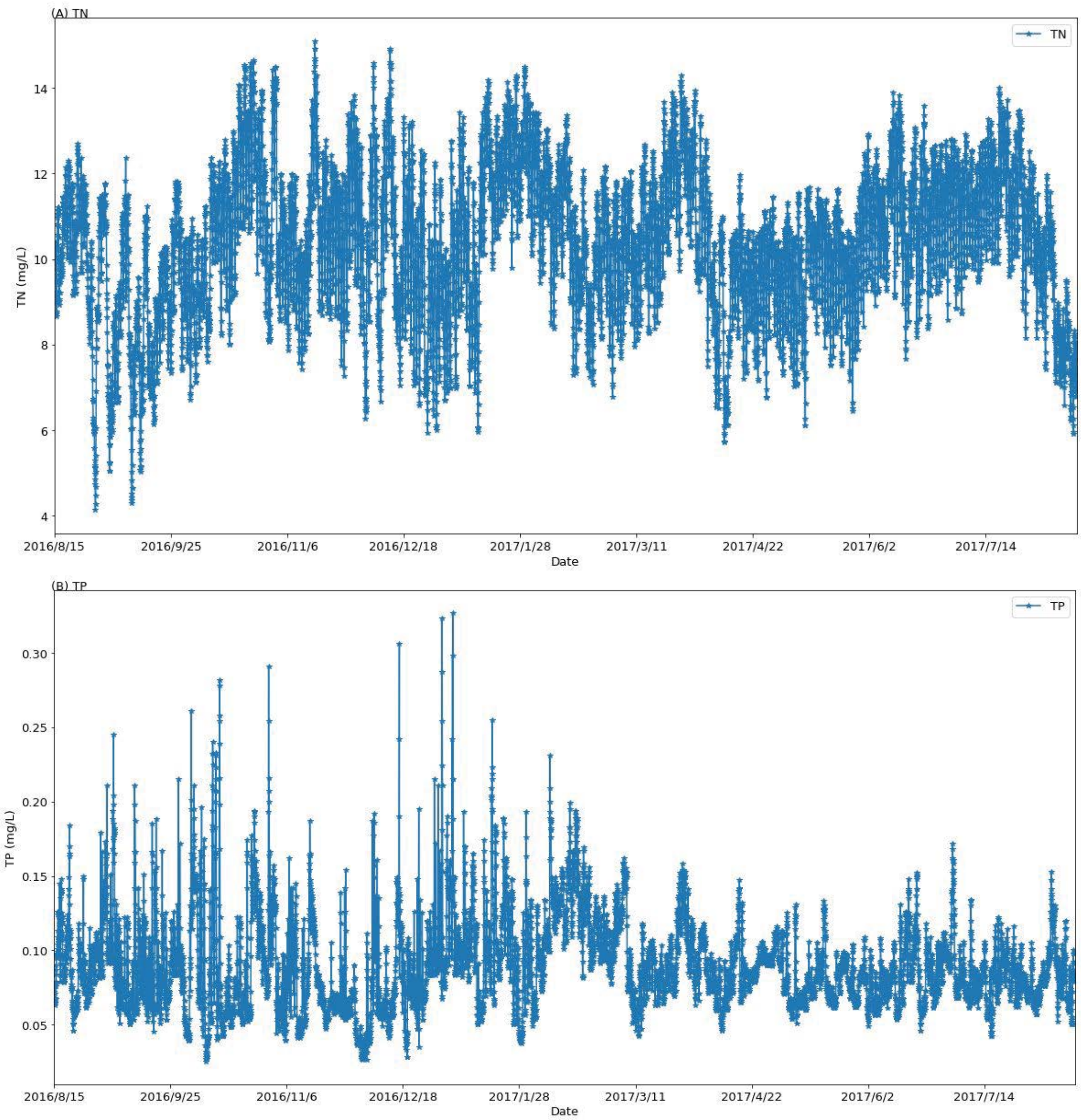

Fig. 6. Hourly TN and TP concentration in the effluent for six months before and after PAC dosage.

A considerable change in TP concentration before and after PAC dosage was indicated as minimum fluctuation was noticed after the PAC application as presented in Fig. 6. The recycling water mostly contains a high load of TN, TP and SS concentration. It is clearly noticed that there was no significant impact on SS but the removal of TN and TP was overall improved that may be associated with the application of PAC that resulted in chemical precipitation of nutrients. Literature studies supported that TP removal was improved significantly in a SBR using PAC [32] and a pilot plant study on anoxic/oxic membrane bioreactor also presented similar results [33]. Therefore, PAC can be an economically and environmentally sustainable alternative to the commercially available LPC for the sludge treatment at full-scale WWTP.

3.4. Economic evaluation

The comparative studies of coagulants consumption cost, their effect on sludge production and water quality parameters such as TN, TP, COD and SS. It was found that the cost per ton of sludge treatment was decreased by 15% when PAC in combination with PPC was used rather than LPC without an increase in sludge production. Additionally, the removal efficiency of TN was improved significantly while a slight increase in TP removal was also noticed while no prominent impact on COD and SS was reported. Therefore, results demonstrated that PAC in combination with PPC can be an economical and environmentally sustainable alternate to LPC for the treatment of sludge at full-scale WWTP.

4. Conclusion

The economic potential of PAC for sludge treatment and its impacts on the sludge production was explored. The effects of mixing recycling water generated in the sludge treatment with influent on to the nutrients, COD and SS removal efficiency of a full-scale WWTP was investigated. Comparative cost-analysis of PPC, LPC and PAC was made during the years of 2016–2019. Coagulant cost per ton of sludge treatment for commercial coagulants PPC and LPC was higher in the year of 2016 while it dropped by 15% in the following years after changing LPC with PAC. Average sludge production was not affected due to the replacement of LPC with PAC. TN removal efficiency was improved by 6% while a 1% increase in TP removal was noticed. A slight drop in COD and SS removal was noted throughout the period may be associated with the mixing of recycling water generated in the sludge treatment section that is loaded with PAC. Although COD and SS removal were dropped slightly, their concentration in the effluent was within set standards. PAC can be used for sludge treatment to decrease the operational cost, to improve the nutrient removal for the environmentally sustainable solution by minimizing fluctuation of TP concentration in the effluent of a full-scale WWTP.

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