Desalination and Water Treatment
www.deswater.com

22 (2010) 292–298
October

doi: 10/5004/dwt.2010.2150

Importance of EBPR efficiency on energy demand of full-scale wastewater treatment plants

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Received December 22 2009; Accepted June 2 2010

ABSTRACT

Enhanced biological phosphorus removal processes (EBPR) are one of the most popular methods in nutrient control. Energy demand of wastewater treatment plants (WWTPs) is also very critical actual concern. In this study, relationship between fundamental characteristics of EBPR and energy demand was investigated in a large scale WWTP. Freshly collected wastewater and activated sludge samples were used in all experiments to obtain accurate results. Effect of both temperature and salinity on air demand in biological stages, which has the most significant impact on energy demand, were also considered in modeling efforts to obtain comparable results. Interactions between energy and soluble carbonaceous biochemical oxygen demand ($sBOD_5$) removed by denitrifies in anaerobic and anoxic zones; acetate uptake rate were evaluated statistically using linear regression model. Effect of salinity on effluent PO_4-P concentration and energy demand were also investigated by field-based measurements and obtained results evaluated statistically. ANOVA tests were also applied to assess acceptability of models from a statistical perspective. Obtained results indicated that EBPR processes would provide significant amount of energy savings in addition to adequate treatment efficiency.

Keywords: EBPR; Energy recovery; $sBOD_5$; Electron acceptor; Acetate uptake; Salinity

1. Introduction

As a result of increasing energy demand and global climate changes, use of energy saving processes became very important criteria in worldwide. Enhanced biological phosphorus removal (EBPR) processes are still one of the most popular methods in wastewater treatment sector [1,2]. Wastewater management in İzmir city, which has a population of 3.3 million, is mainly based on EBPR processes. Approximately, 229 million m^3 of domestic and industrial wastewater are treated in the city annually. In addition, more than 97% of wastewater is treated through EBPR processes to improve the water quality of İzmir Gulf, which had been exposed to serious domestic and industrial pollution until 2000. Central wastewater treatment plant (WWTP) of İzmir city that was designed to serve 3.5 million population equivalent was taken into operation in 2000. Currently, 16 municipal WWTPs have been under operation. As an expected consequent of increasing number of WWTPs, establishment of a sustainable sludge management model is one of the actual concerns for the city.

Mechanism of EBPR is based on selection of phosphorus accumulating microorganisms (PAOs) within the process by exposing the activated sludge into anaerobic–anoxic–aerobic environments [3]. Proliferation of desired microorganisms in the system is attributed to energy conversion ability of these microorganisms from

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breakage of intracellular poly-P [4,5]. Energy, derived from poly-P degradation is used for storage of simple carbon sources as polyhydroxyalkanoates (PHA) in the cell inventory. Utilization of these polymeric intracellular compounds in the following oxidative zones generates required energy for reproduction of new cells and restoring depleted poly-P reserves [6,7,8]. It was also reported that phosphorus is removed in anoxic zone via denitrification reactions in which internally stored PHA is used as electron donor [6,9].

Several environmental and operational factors, including type and amount of influent carbon source, pH, temperature and solids retention time (SRT) in the biological system would have significant impact on the process performance. Furthermore biochemical reactions taking place in the anaerobic phase could be determinative on overall nutrient removal performance of WWTP [9]. Moreover this short anaerobic reaction period, varying between 0.5–2 h would also determine the efficiency of remaining 4–16 hours-oxidative period [10,11].

Although energy saving potential of EBPR processes had been reported previously, a model-based full-scale experimental investigation has never been conducted or reported. Therefore, main objective of the present paper is to investigate possible interactions between energy demand and the amount of removed organic load, which was represented as $sBOD_5$, through the anaerobic–anoxic biochemical reactions in a full-scale EBPR process. In addition to $sBOD_5$ removal, anaerobic acetate uptake rate were also included in modeling efforts. Effect of salinity on energy demand and effluent PO_4-P concentration were also analyzed statistically using long-term operational data.

Investigations were carried out in İzmir WWTP from winter to autumn seasons of 2009. In order to evaluate the EBPR process accurately, wastewater were characterized for COD, BOD, VFAs, nitrogen, phosphorus and their various fractions. Temperature, pH and DO parameters were also monitored continuously in each step of EBPR process. Mass balances were established around anaerobic–anoxic-aerobic zones, return activated sludge line and final clarifiers. Flow rates and electricity usage were also monitored by online systems continuously. Oxygen consumption (air demand) was corrected for temperature (20 °C) and salinity as described in the literature [12,13].

2. Material and methods

2.1. The process configuration

WWTP was designed to treat domestic and industrial wastewater having average flow rate of approximately 605,000 $m^3 d^{-1}$. In the plant, wastewater first comes to pre-treatment units which consist of fine screens, aerated grit chambers and circular primary sedimentation tanks. Following the grit removal process, wastewater is distributed equally to three treatment lines. In each one of these independent treatment lines, wastewater is settled in primary clarifiers. Following the primary sedimentation, the EBPR process starts with the anaerobic tanks. In these tanks, settled wastewater comes into contact with microorganisms carried by the return activated sludge line. After this anaerobic contact period, wastewater is exposed to anoxic and aerobic conditions in oxidation ditches for combined removal of carbon, nitrogen and phosphorus. Biomass and effluent phases are separated in circular final clarifiers. Settled sludge is collected in a chamber from where it is returned to the anaerobic tanks (fig .1).

Start and end of the anaerobic, anoxic and aerobic zones, return activated sludge line and effluent of final clarifiers were selected as sampling points. Samples were collected periodically as flow portioned. As chemi-

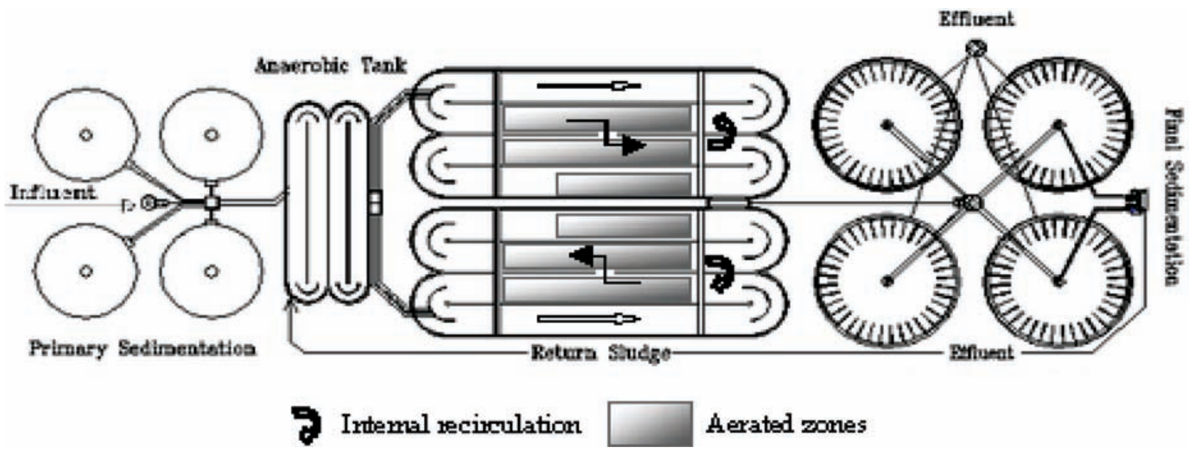

Fig. 1. Simplified flow diagram of EBPR process.

cal characteristics of the samples (both wastewater and activated sludge) are very unstable, the period from sampling to analysis were kept as short as possible. To obtain more accurate analysis results, samples for soluble forms including VFAs, phosphate, nitrate and ammonium were filtered immediately at the sampling points using single use syringe filter that has a pore size of 0.45 μm.

2.2. Analytical and experimental methods

The 2 l Woulf Bottles (Woulff'sche-Flaschen, DURAN®, Schott) were used to perform the batch tests. Mixing was provided by a magnetic stirrer. N_2 gas was fed to the reactor by a diffuser from N_2 tube in anaerobic and anoxic batch tests. Anoxic conditions were maintained by the addition of surplus amount of nitrate (24 ± 0.2 mg l^{-1} NO_3–N) at the beginning of the test. All of the experiments were conducted at a controlled temperature of 20 ± 0.5˚C and pH of 7.0 ± 0.3. Freshly collected effluent and activated sludge samples were obtained from the treatment plant return sludge pumping station. A portion of the effluent, acetate and activated sludge were placed into the reactor. Volumetric mixture ratio between effluent, acetate and activated sludge were determined according to the actual F M^{-1} ratios of the treatment plant. Samples were taken periodically at 1, 5, 10, 15, 20, 30, 60 and 90 minutes and PO_4-P, VFAs and VSS concentrations were measured to determine the acetate uptake rate. At the end of the test, surplus carbon always remained in solution to be sure that carbon did not limit phosphorus release [14,15].

BOD_5 test is performed by respirometric methods in which pressure difference were measured automatically by the aid of lithium hydroxide. COD measurement was based on reaction of oxidizable substances with sulphiric acid–potassium dichromate solution including silver sulfate as a catalyst. VFAs concentration is determined according to reaction between fatty acids and diols in an acidic environment, resulting with formation of fatty acid esters. Total nitrogen concentration is determined photometrically by oxidizing inorganically and organically bonded nitrogens to nitrate with peroxide-sulphate. The method used in determination of ammonium concentration is based on reaction of ammonium ions with hypochlorite and salicylate ions in the presence of sodium nitroprusside as a catalyst to form indophenols blue. Nitrate concentration was determined according to the reaction of nitrate ions with 2.6-dimethylphenol in sulfuric and phosphoric acid medium to form 4-nitro 2.6-dimethylphenol. Phosphate measurement was based on reaction of phosphate ions with molibdat and antimony in an acidic solution to form antimony phosphomolibdat complex. Suspended solids (SS), mixed liquor suspended solids (MLSS) and MLVSS were measured according to Standard Methods [16]. pH and temperature were measured using well calibrated probes. Flow rates and electricity usage were also monitored by online systems continuously. Energy demand was standardized for temperature (20˚C) and salinity as described in the literature [12,13]. It should be also stated that acetate uptake could be executed by several microbial groups. Nevertheless this study mainly focuses on assessing the energy demand and facultative removal of soluble organic load in the anaerobic and anoxic zones without considering responsible microbial cultures.

2.3. Statistical analysis

In this study interactions among the studied parameters including energy consumption, $sBOD_5$ removal, acetate uptake rate and salinity were analyzed using linear regression model which assumes that there is a linear, or "straight line," relationship between the dependent variable and each predictor. This relationship is described in the Eq. (1).

$$y_i = b_0 + b_1 x_{i1} + \cdots + b_p x_{ip} + e_i \quad (1)$$

where y_i is the value of the ith case of the dependent scale variable; p is the number of predictors; b_j is the value of the jth coefficient, $j = 0, ..., p$; x_{ij} is the value of the ith case of the jth predictor; e_i is the error in the observed value for the ith case.

The model is linear because increasing the value of the "j"th predictor by 1 unit increases the value of the dependent "b_y"; "b_j" units. b_0 is the intercept, the model-predicted value of the dependent variable when the value of every predictor is equal to zero. The ANOVA test was also performed to evaluate acceptability of the models from a statistical perspective. Trial version of SPSS® v.13 software was used for all data analysis.

3. Results and Discussion

3.1. Wastewater composition and loading conditions

Results of similar full scale studies proposed that organic composition of wastewater could influence EBPR performance significantly [8,17]. It has been also reported that ratio of volatile fatty acids (VFAs) to total phosphorus (TP) – (P $VFAs^{-1}$) was 0.12 averagely and effluent TP was lower than 1 mg l^{-1} [8]. According to the wastewater characterization results that were given in Table 1, level of carbon source was nearly optimum for a stable EBPR performance. P $VFAs^{-1}$ ratios ranged from 0.10 to 0.16 mg mg^{-1}in the period of study. rbsCOD concentration at the start of the anaerobic phase ranged from 108.8 to 142.4 mg l^{-1}. In addition, there was positive

Table 1
Wastewater characteristics prior to anaerobic phase

Parameter	Dimension	Concentration
BOD_5	mg l^{-1}	175 ± 55.2
$sBOD_5$	mg l^{-1}	120 ± 11.2
VFAs	mg l^{-1}	56 ± 13.5
Total nitrogen	mg l^{-1}	36 ± 5.4
Total phosphorus	mg l^{-1}	8 ± 1.9
Salinity	‰	4.3 ± 2.1

correlation (R^2 > 80) between concentrations of VFAs and BOD_5, COD and readily biodegradable COD (rbsCOD).

Total nitrogen and ammonium concentrations at the start of the anaerobic phase were 36 ± 5.4 and 21 ± 2.9 mg l^{-1}. Salinity level of wastewater was also measured continuously and it was higher than typical characteristics of typical wastewater. Average salinity and conductivity level of raw wastewater were determined to be 5.3 ± 2.1‰ and 7.4 ± 3.2‰. Interactions between salinity, energy demand (unstandardized) and effluent PO_4-P concentration were investigated statistically using 810 data compiled from field-based measurements. Strength of interactions among the studied parameters was summarized in Table 2. Obtained value of multiple correlation coefficients for both relationships were 0.104 and 0.112. These results indicated that approximately 90% of variations could not be explained by the model.

According to the Anova test results, obtained sum of squares for regressions was also lower than 2% indicating variations in effluent PO_4-P concentration and energy demand could not be explained by the variations in salinity. Consequently it could be safely concluded that other operational and environmental factors; including temperature, organic load to the biological stages and sludge age would have much more significant impact on EBPR as compared to salinity. The plot of residuals by the predicted values, depicted in Fig. 2 clearly indicated that variances in residual errors were also significant.

Average VFAs (acetate) uptake rate, P release rate and P $VFAs^{-1}$ ratio were determined to be 17.8 ± 1.9 mg VFAs

Table 2
Strength of correlation between salinity, energy demand and effluent PO_4-P concentration

Relationship	R	R^2	Adjusted R^2
Salinity – energy demand	0.323	0.104	0.101
Salinity – effluent [PO_4-P]	0.334	0.112	0.108

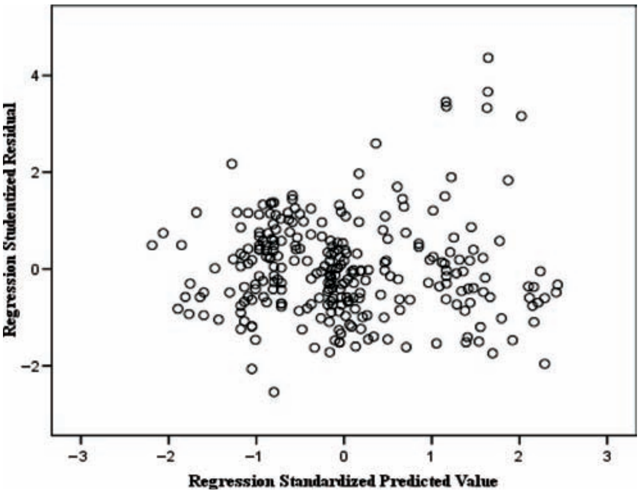

Fig. 2. Residual errors between predicted and observed values.

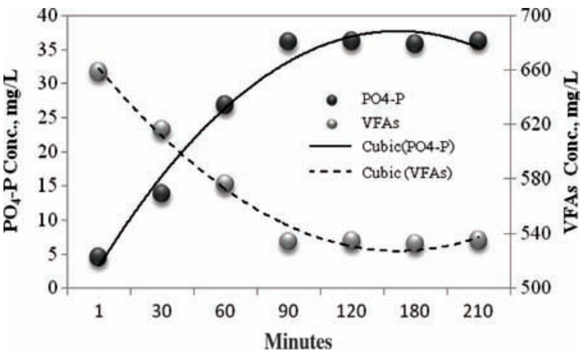

Fig. 3. Utilization of simple substrate forms in anaerobic EBPR reactions by the aid of PO_4-P release into bulk interface.

(as acetate) (gVSS $h)^{-1}$, 16.2 ± 1.1 mg PO_4-P (gVSS $h)^{-1}$ and 0.25 ± 0.1 mg P HAc^{-1} from batch tests. It is evident from Fig. 3 that significant amount of simple substrate forms (acetate) was degraded by the activated sludge culture using the energy, generated from PO_4-P release. In full-scale EBPR processes, simple substrate forms are converted to short chain fatty acids (VFAs) in anaerobic phase as well. Therefore both already existing and newly generated VFAs are stored in the anaerobic phase by the microorganisms. These intracellular storage compounds were used to generate the energy required for new cell synthesis, maintenance and restore of depleted polyphosphate polls in the following anoxic zone by the aid of internally produced nitrate [9]. According to the measurement results, average concentration of $sBOD_5$ and VFAs in raw wastewater were 120 ± 11.2 and 56 ± 13.5 mg l^{-1} in the period of study.

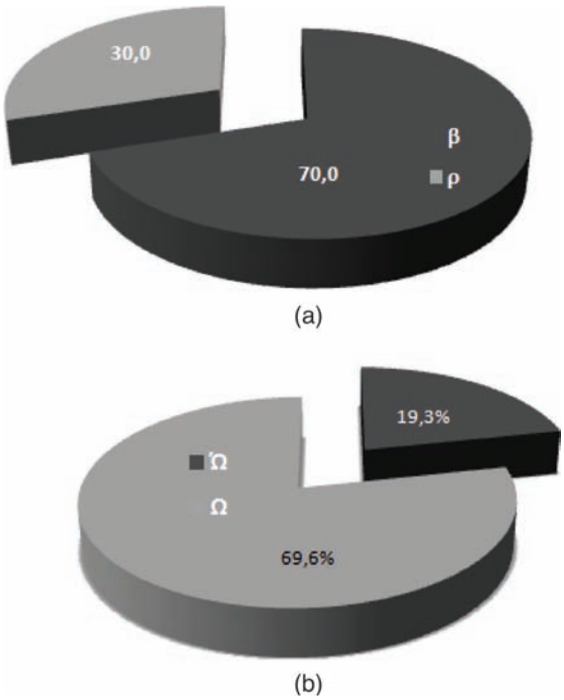

Fig. 4. (a) Percentages of BOD_5 removal by primary sedimentation (ρ) and biological treatment (β). (b) Percentages of $sBOD_5$ removal by electron acceptors (in anaerobic phase) (Ω) and denitrifiers (in anoxic phase) (Ω).

It has been also reported that biodegradable suspended compounds could also be utilized in anoxic zone by DPAOs [9]. To estimate the amount of $sBOD_5$ removed by denitrifiers in both anaerobic and anoxic zone, all of the electron acceptor mass fluxes were defined as nitrate using the theoretical conversion factor of 2.86 gO_2 gNO_3-N^{-1} [12]. Ratio of $sBOD_5$:NO_3-$N_{removed}$ was experimentally determined and used to estimate total amount of $sBOD_5$ removed in the anaerobic and anoxic zones of the process. The ratio varied from 8.1 to 9.0 in the period of study. Total concentration of electron acceptors (ΣEA) varied from 0.9 to 3.3 mg l^{-1}. Furthermore 75.6 ± 2 % of ΣEA was in the form of DO.

3.2. *Modeling the energy demand as a function of $sBOD_5$ removal and acetate uptake rate*

Energy consumption (monthly) and acetate uptake rate were measured to be 2,782,457 ± 635,218 kwh and 21.5 ± 3.2 mg acetate g VSS^{-1} h^{-1}. Averagely, 3509 ± 865 t BOD_5 loaded to the plant and 3210 ± 924 t of BOD_5 removed by primary and biological treatment. Average amount of biologically (by EBPR reactions) removed BOD_5 was 2247 ± 101 t. Electron acceptor mass fluxes to the anaerobic phase from both influent and return sludge lines were significant. Furthermore, in each set of full scale experimental runs, effluent of the anaerobic tank contained negligible amount of DO (0.1 ± 0.1 mg l^{-1}) and nitrate (<0.01 mg l^{-1}) indicating the magnitude of facultative activity taking place in the anaerobic phase. Total mass fluxes of electron acceptors at the start of anaerobic phase were determined to be 76 ± 4.5 t d^{-1}. Consequently, 633 ± 41 t $sBOD_5$ removed by electron acceptors. Measured average quantity of $sBOD_5$ removed in denitrification reactions (in anoxic zone) was 433 ± 62 t. Therefore, total amount of $sBOD_5$ removed by denitrifiers without using dissolved oxygen was 1066 ± 52 t. According to these estimations, averagely, 52% of the influent BOD_5 would be removed without requiring dissolved oxygen. Field-based measurement results also indicated that all of the rbsCOD was depleted in the anaerobic phase (Fig. 4).

Correlation between energy demand and acetate uptake rate; $sBOD_5$ removal (removed $sBOD_5$ both in anaerobic and anoxic zones) was investigated statistically using linear model. Total monthly mass fluxes of energy; $sBOD_5$ and anaerobic acetate uptake rate were the input of the model. Multiple correlation coefficient (R) and coefficient of determination (R^2) of the developed model were 0.981 and 0.963. These high regression coefficients indicated that increasing acetate uptake rate and the amount of $sBOD_5$ removed by denitrifies decreased energy consumption used in the WWTP significantly. According to the Anova test, the significance value of the F statistic (52.352) is less than 0.05, which means that the variation explained by the model is acceptable. Coefficients obtained from the model were also summarized in Table 3.

As it could be seen in Fig. 5 (5a and 5b), the P-P plotted residuals also followed the 45-degree line and histogram followed to normal distribution curve. These results also indicated that normality assumption was not violated and there were strong relationship between the studied parameters. Furthermore it could be safely concluded that increasing $sBOD_5$ quantity, removed by denitrifiers and anaerobic acetate uptake rate decreased the energy consumption of the plant.

Table 3
Coefficients obtained from the model

Model	Unstandardized coefficients		Standardized coefficients	t	sig.
	B	Std. Err.	β		
(Constant)	9147145	850546,3	–	10.754	0.000
Acetate uptake rate	–435267	146933,5	–1.290	–2.962	0.041
sBOD5 (removed)	3289.654	4492,784	0.319	0.732	0.505

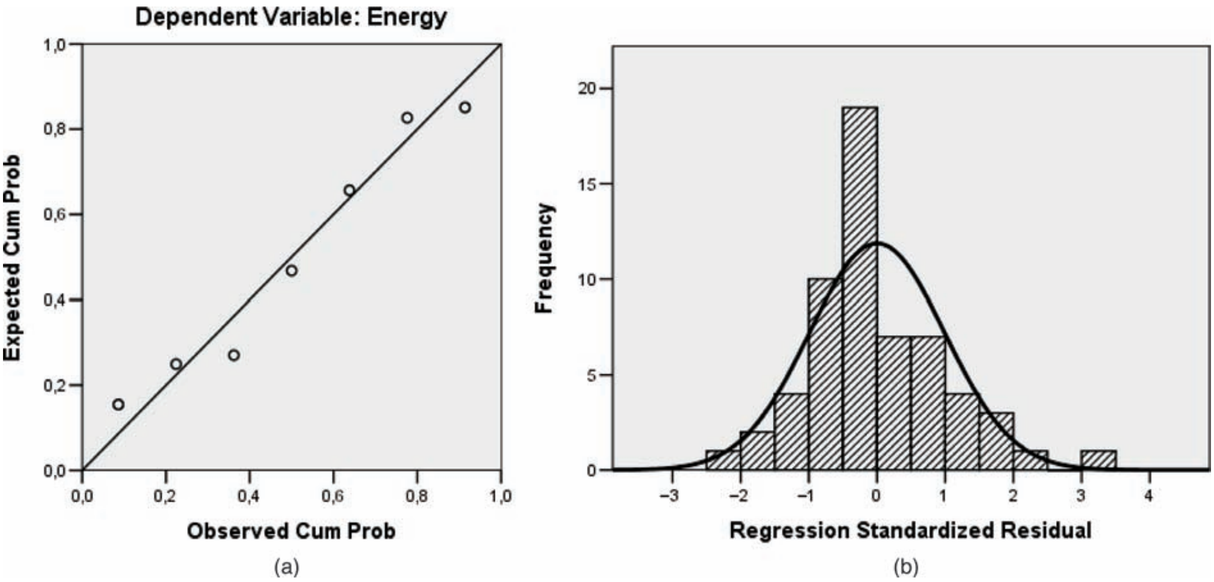

Fig. 5. (a) Expected and measured (observed) cumulative probability (b) Normality assumptions and histogram.

4. Conclusion

In this study, interactions between energy demand and fundamental characteristics of EBPR were investigated by full-scale research. Conducted batch and field based tests clearly indicated that significant amount of soluble carbonaceous substrate forms would be removed in EBPR process without requiring external oxygen supply thus leading considerable amount of energy recovery. Fundamental mechanisms of energy recovery could be explained with electron acceptors being loaded to the anaerobic phase from both influent and return sludge streams which intern lead to degradation of simple substrate forms by microorganisms. The second pathway of energy recovery would also be attributed to utilization of complex polymers of polyhydroxybutyrate, polyhydroxyvalerate and their methylated forms in the anoxic phase by the aid of nitrate. The level of energy recovery could be a function of readily biodegradable substrate forms present in influent and operational conditions of EBPR process. Main conclusion that could be withdrawn from the presented research is use of EBPR processes could not only provide with adequate control of effluent phosphorus level but also provide with improvement of overall operational conditions including energy saving as well.

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