Environment Protection Engineering

Vol. 45 2019 No. 1

DOI: 10.5277/epe190101

NESLIHAN MANAV DEMIR[1], ASUMAN YILDIRIM[1],
TAMER COSKUN[1], CIGDEM BALCIK CANBOLAT[1], EYUP DEBIK[1]

CARBON AND NUTRIENT REMOVAL FROM DOMESTIC WASTEWATERS IN A MODIFIED 5-STAGE BARDENPHO PROCESS VIA FUZZY MODELING APPROACH

Gradual increase in the generation of wastewater results from the increasing global population. Thus, new treatment techniques and systems for controlling the treatment process depending on wastewater characteristics are desirable. This paper presents the use of a pilot-scale modified five-stage Bardenpho process with a 10 m^3/day capacity for the treatment of real municipal wastewater. The process was developed for this study, and the steady-state removal efficiencies for COD (chemical oxygen demand), TKN (total Kjeldahl nitrogen), NH_4^+-N (ammonium nitrogen), PO_4^{3-}-P (phosphate phosphorus), SS (suspended solids), and VSS (volatile suspended solids) were 87±5%, 86±12%, 93±14%, 89±9%, 88±8%, 94±4%, and 94±4%, respectively. In the study, the effluent COD, TKN, and TP concentrations were also estimated using a fuzzy logic approach. The results showed that coefficients of determination are higher than 0.80 suggesting that the presented fuzzy logic approach may confidently be used for the estimation of the treatment performance.

1. INTRODUCTION

Wastewater generation has been gradually increasing as a result of increase in global population and industrialization. Domestic wastewaters are composed mainly of organic materials, nutrients (phosphorus and nitrogen) [1], suspended solids, sediment, and several pathogenic microorganisms [2] that live in the human intestinal tract. Wastewater treatment plant is designed for obtaining higher treatment efficiencies [3] and producing high quality effluent after treatment [4]. Though advances in wastewater treatment techniques allow higher treatment efficiencies and compliance of stringent effluent limits, challenges still exist pertaining to improvement of current treatment techniques especially in developing countries [5]. The selection process for a waste-

[1]Yildiz Technical University, Faculty of Civil Engineering, Environmental Engineering Department, 34220, Esenler, Istanbul, Turkey, e-mail address: nmanav@yildiz.edu.tr

water treatment system has the limitations in, most importantly, economical and technical aspects. Besides, climatic conditions, energy requirements, and other environmental factors make this selection process more complicated. Also, detailed information on environmental requirements for distinct treatment options are required for a more efficient selection [6]. To remove carbon and nutrients from domestic wastewaters, the current literature describes many treatment designs, including, but not limited to, upflow anaerobic sludge blanket-activated sludge (UASB-AS) reactors, upflow anaerobic sludge blanket-sequencing batch reactors (UASB-SBR), sequencing batch reactors (SBR), anaerobic/anoxic/oxic-biological aerated filters (A^2O-BAF), anoxic/oxic (AO) reactors, anaerobic/anoxic/oxic (A^2O) reactors, modified University of Cape Town (modified UCT) reactors, cascade-feed University of Cape Town (cascade-feed UCT) reactors, cascade-feed anaerobic/anoxic/oxic (cascade-feed A^2O) reactors, anaerobic/anoxic/oxic membrane bioreactors (A^2O-MBR), and five-stage Bardenpho reactors [7].

Unfortunately, there is no proper, efficient, or sufficient WWTP in everywhere of Turkey, although legislation requires the treatment of domestic wastewaters prior to discharge. According to the 2014 statistics, only 64% of Turkish population was offered wastewater treatment service with a total of 604 wastewater treatment plants, only 92 of which is of advanced biological treatment systems that meet treatment objectives in EU standards [8]. Thus, advanced biological treatment processes are applied to only 41.6% of total discharge. *Legislation on Urban Wastewater Treatment* has been set on January 8th, 2006 within European Union integration framework of legislations [9] which enabled construction of new sewage systems and wastewater treatment plants. Besides, the same action plan aims to increase the percent of urban population that benefits from sewage systems and wastewater treatment plants to over 90% in cities of over 50 thousand capita by the year 2020 [10]. According to the *2015–2023 Action Plan by Turkish Ministry of Environment and Urbanization*, a total of 1501 (1418 new plants and 83 rehabilitated plants) wastewater treatment plant will be installed [11]. Besides, Turkish Ministry of Environment and Forestry plans to develop reconstruction of wastewater treatment plans and rehabilitation of sewage systems until 2024. The plans are based on the minimum-cost scenarios with proper treatment technologies that are required depending on wastewater characteristics [12]. Therefore, the selection of the best treatment process optimized for performance and cost is of great importance for Turkey as well as for developing countries.

Modeling approaches provide useful tools for easy system control and operation considering the complexity of biological processes and several operational problems. For this purpose, this study focuses on the use of a fuzzy logic approach for modeling treatment performance in a developed pilot-scale system. The fuzzy logic model was first developed by Zadeh in 1965 [13]. Most computer models for treatment processes are run on digital platforms and involve zeros and ones (false and true, respectively). However, the human brain is analog and presents options other than those that are strictly true or false. Fuzzy logic allows analog measures for both analog and digital data. Thus, fuzzy models provide the computer ability to calculate and take analog actions, similar to the human brain [14].

A fuzzy model comprises three stages: fuzzifier, inference, and defuzzifier [15]. A fuzzy model also includes a database for rules and membership functions. The fuzzifier converts the input data into a fuzzy input set. The fuzzy inputs are the values of the membership functions, which can be triangular, trapezoidal, sigmoidal, Gaussian, or bell-shaped functions [16]. The membership values are then evaluated according to the rules in the database, and the fuzzy results are defuzzified in the defuzzifier. In the context of environmental management, the use of the fuzzy logic method is strongly suggested [17].

This study aims to investigate the effects of modifying a five-stage Bardenpho process on carbon and nutrient removal performance. The pilot-scale process involves aerobic2 and aerobic1 zones of equal volume and an internal recirculation from aerobic2 zone to anoxic2 zone in order for aerobic2 zone to actively participate in the treatment of domestic wastewaters. A fuzzy model was also established to assess the applicability to predict and control the removal of biological carbon and nutrients from domestic wastewaters.

2. MATERIALS AND METHODS

2.1. PILOT SCALE TREATMENT PLANT

The pilot-scale modified five-stage treatment plant was installed in Ataköy Biological Wastewater Treatment Plant of Istanbul Water and Sewerage Administration (Istanbul, Turkey). The pilot-plant was fed with the effluent from the grit removal units of the installed full-scale, domestic wastewater treatment plant. The characteristics of the wastewater are displayed in Table 1 along with descriptive statistics.

Table 1

The characteristics of the raw domestic wastewater

Parameter	Mean value[a]	STD[b]	Min.	Max.
COD, mg O_2/dm^3	647	113	465	930
TKN, mg/dm^3	79	13	39	100
NH_4^+-N, mg/dm^3	52	9	34	68
NO_2^--N, mg/dm^3	0.04	0.03	0.01	0.15
NO_3^--N, mg/dm^3	0.11	0.10	0.01	0.40
TN, mg/dm^3	79	13	40	100
TP, mg/dm^3	7.9	0.8	6.5	10.3
PO_4^{3-}-P, mg/dm^3	3.4	0.7	1.7	4.9
SS, mg/dm^3	321	156	119	879
VSS, mg/dm^3	220	67	92	402

[a]Average value in 37 samples.
[b] STD – standard deviation from 37 data points.

The data shown in the table are results of analyses of influent samples (2 samples/week) taken for a period of 19 weeks, and all of the analyses were performed with three replicates. The average influent COD (chemical oxygen demand) was 647 mg O_2/dm^3 with a negative skewness around the mean. Same negative skewness was also observed for TKN (total Kjeldahl nitrogen), NO_3^--N (nitrate nitrogen), TN (total nitrogen), TP (total phosphorus), PO_4^{3-}-P (phosphate phosphorus), SS (suspended solids), and VSS (volatile suspended solids) concentrations. The plant was inoculated with the sludge from the return activated-sludge line of the full-scale plant.

Mechanical mixers were employed in anaerobic and anoxic tanks to prevent the sludge from settling. Four diffusers were used for each aerobic tank for aeration and mixing purposes. The return activated sludge was withdrawn from the secondary sedimentation tank to the anaerobic tank. The volumes, hydraulic retention times (HRT), recycle ratios, and other operational parameters for each tank are summarized in Table 2.

Table 2

The design and operational parameters
of the developed pilot scale treatment plant [7]

Phase	Number	Volume [m^3]	HRT [h]
Primary clarifier	1	0.25	0.6
Distribution tank	1	0.25	0.6
Anaerobic tank	1	0.5	1.2
Anoxic tanks	2	1.4	3.36
Aerobic tanks	2	1.7	4.08
Secondary clarifier	1	1.4	3.36
Biological nutrient removal	–	6.7	16.08
Total	–	8.6	20.64
Operational parameters		Value	
Influent flow Q, m^3/day		10.0	
Recycling flow, Q_R, m^3/day		8.0	
First internal recycle flow, Q_{R1}, m^3/day		43.0	
Second internal recycle flow, Q_{R2}, m^3/day		47.0	
DO_{Ox}, mg O_2/dm^3		2.0–2.5	
pH		7.57±0.19	
Mixed liquor suspended solids, MLSS, m^3/dm^3		4500–5500 mg/dm^3	
SVI		120±15 cm^3/g	

The pilot-scale plant had a capacity of 10 m^3/day and consisted of an inlet structure (including screens), a primary sedimentation tank, a distribution tank, an anaerobic/anoxic1/aerobic1/anoxic2/aerobic2 process configuration, and a secondary sedimentation tank. The main difference of this pilot-scale process from the conventional five-stage Bardenpho process lies in the internal recirculation from aerobic2 to anoxic2 process and the equal volumes of aerobic1 and aerobic2 zones. The flow diagram of the process is given in Fig. 1.

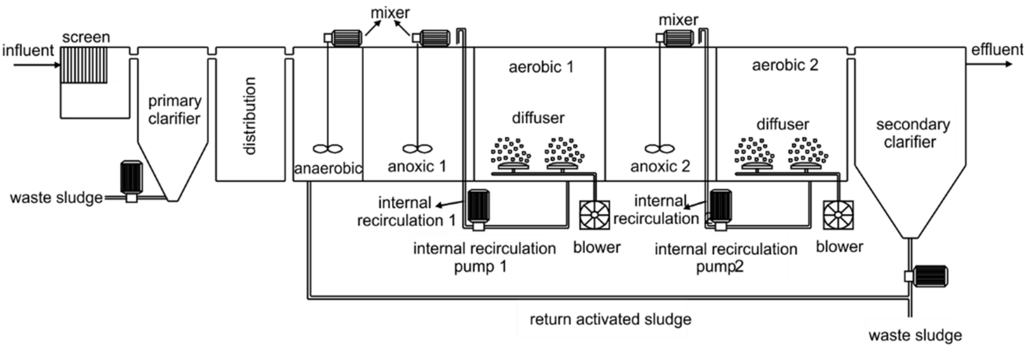

Fig. 1. Schematic diagram of the developed pilot-scale treatment plant [7]

2.2. ANALYTICAL METHODS

The analyses of COD, TKN, NH_4^+-N, NO_3^--N, NO_2^--N, TP, and PO_4^{3-}-P were performed according to standard methods. COD in the pretreated wastewater (feed water) and in the effluent was measured by the open reflux method (5220-B). The NH_4^+-N and TKN measurements were conducted by the 4500-NH_4^+-C and 4500-Norg-B methods, respectively. The PO_4^{3-}-P and TP concentrations were determined by the colorimetric method 4500-P using a WTW photolab 6600 UV-VIS (spectroFlex 6600) spectrophotometer. The SS concentration was determined after drying the samples in an aluminum dish at 105 °C overnight. All analytical measurements were performed at least in three replicates.

2.3. THE FUZZY MODEL

A fuzzy model was established to predict and control the treatment performance, and the applicability of the fuzzy approach. The Fuzzy Logic Toolbox in MATLAB™ was used with the Mamdani model.

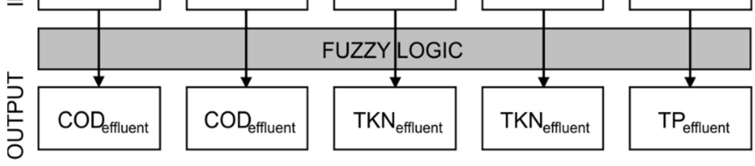

Fig. 2. Inputs and outputs of the fuzzy models

Influent COD, influent TKN, and influent TP concentrations were used as inputs to obtain fuzzy model outputs for effluent COD, TKN, and TP concentrations which established a fuzzy control scheme for the COD and nutrient removal control in the system. The flowcharts of the five models are shown in Fig. 2.

Five membership functions were employed for each input and output variable. The values of the membership functions were very low, low, average, high, and very high. Table 3 summarizes the ranges of membership functions.

Table 3

Values of membership functions of input and output variables

Membership functions	Input variables		
	COD_{inf}	TKN_{inf}	TP_{inf}
Very low	[400 450 500 550]	[25 35 45 55]	[5.5 6 6.5 7]
Low	[500 550 600 650]	[45 55 65 75]	[6.5 7 7.5 8]
Normal	[600 650 700 750]	[65 70 80 90]	[7.5 8 8.5 9]
High	[700 750 800 850]	[80 90 95 100]	[8.5 9 9.5 10]
Very high	[800 850 900 950]	[95 100 105 110]	[9.5 10.25 11 11.5]
	Output variables		
	COD_{eff}	TKN_{eff}	TP_{eff}
Very low	[–50 0 50 100]	[–10 0 10 20]	[–0.4 0 0.4 0.8]
Low	[50 100 150 200]	[10 20 30 40]	[0.4 0.8 1.2 1.6]
Normal	[150 200 250 300]	[30 40 50 60]	[1.2 1.6 2 2.4]
High	[250 300 350 400]	[50 60 65 70]	[2 2.4 2.8 3.2]
Very high	[350 400 450 500]	[65 70 80 90]	[2.8 3.5 4 4.5]

The rules database involves 300 rules for five models with two conditions as:

if (input1 is ...) and (input2 is ...) then (output1 is ...)

Approximately 70% of the measurement data (27 data points) was used for the rules database and the remaining 10 data points were used for the control purposes.

3. RESULTS AND DISCUSSION

The developed pilot-scale modified five-stage Bardenpho process reached steady state during the ninth week. Before steady state, COD removal efficiencies ranged from 20% to 85% with an increasing trend over time. Similarly, NH_4^+-N, TKN, PO_4^{3-}-P, and TP removal efficiencies were in the ranges 17–93%, 19–88%, 25–90%, and 51– 91%, respectively, with a similar increasing trend over time of operation. However, the measurement results and removal efficiencies from the ninth week on were used for the evaluations. Measurement results during the whole operation period are given in Fig. 3, and the data presented stands for averages of triplicate measurements.

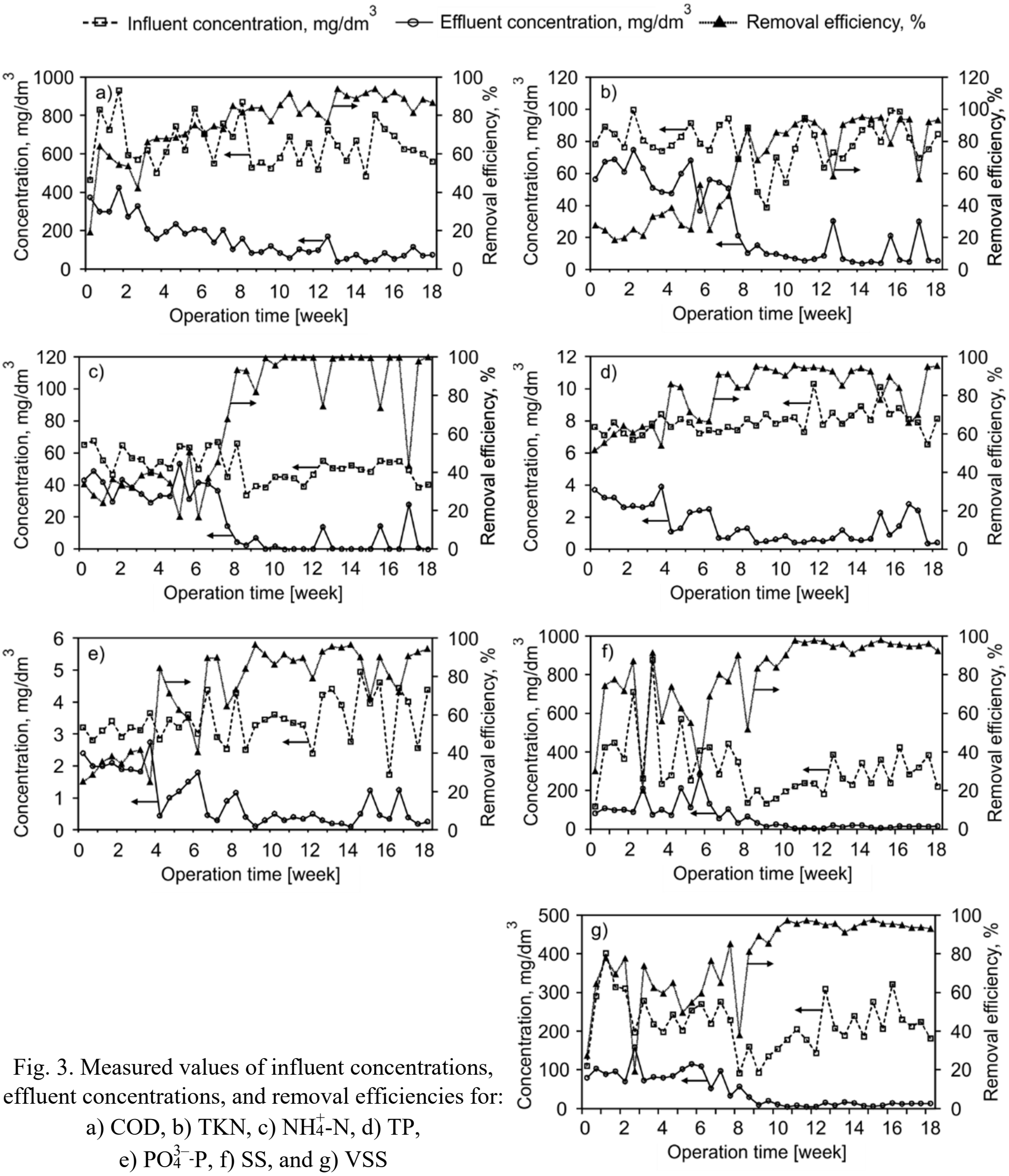

Fig. 3. Measured values of influent concentrations, effluent concentrations, and removal efficiencies for: a) COD, b) TKN, c) NH_4^+-N, d) TP, e) PO_4^{3-}-P, f) SS, and g) VSS

Under steady-state conditions, the minimum, maximum, and average values of the effluent COD concentration were 40, 170, and 81.8±30.9 mg O_2/dm^3, respectively. The COD removal efficiencies ranged from 77% to 94% with an average value of 87±5%. Figure 3a shows the influent and effluent COD concentrations and the removal efficiencies.

The influent and effluent TKN concentrations were measured as 75.9±15.9 and 10.1±8.1 mg N/dm^3, respectively, with an average removal efficiency of 86±12%. The average concentration of NH_4^+-N in the effluent under steady-state conditions was 3.6±7.3 mg N/dm^3, with removal efficiencies in the range of 43–99.8%. The measured values of the influent and effluent TKN concentrations are shown in Fig. 3b along with their respective removal efficiencies. The average NH_4^+-N removal efficiency was 93±14%. Figure 3c displays the change of the influent and effluent NH_4^+-N concentrations and the removal efficiencies. The average influent NO_2^--N and NO_3^--N concentrations were 0.05±0.03 mg N/dm^3 and 0.13±0.11 mg N/dm^3, respectively, with corresponding effluent concentrations of 0.65±0.57 mg N/dm^3 and 2.08±0.54 mg N/dm^3, respectively.

The influent and effluent concentrations of TP were measured as 8.3±0.8 and 0.9±0.7 mg P/dm^3, respectively, while those of PO_4^{3-}-P were 3.6±0.9 and 0.4±0.3 mg P/dm^3, respectively. The average removal efficiencies were calculated as 89±9% for TP and 88±8% for PO_4^{3-}-P. The measured concentrations of TP and PO_4^{3-}-P are shown in Figs. 3d and 3e, respectively, along with their respective removal efficiencies.

Table 4

Comparison of the results from current study with the literature data

Reactor		Wastewater	HRT [h]	Removal efficiency, %						Ref.
Type[a]	V [m^3]			COD	TN	NH_4^+-N	TP	PO_4^{3-}-P	SS	
Modified 5-stage Bardenpho	8.6	domestic	16.08	87	82	93	89	88	94	present
5-stage BNR	16.2	municipal	7.5	87.0	79.0	88.0	–	87.0	90.0	[18]
MBR_p	0.24	municipal	18	82.70	58.96	–	74.38	–	94.82	[19]
Hybrid MBBR-MBR_{ap}				85.82	58.13	–	81.42	–	95.78	
Hybrid MBBR-MBR_{bp}				83.18	61.39	–	76.44	–	94.66	
UCT–MBR	0.375	municipal -synthetic	20	98.4	58.1	–	–	70		[20]
				72.9	31.5	–	–	–	–	
Step-feed	0.0223	domestic	16	95	93	95	78	–	–	[21]
AOA	0.043	synthetic	8	–	70.3	93.0	–	87.3	–	[22]
AAO-BCO	0.076	domestic	6	78.26	57.32	89.05	87–95	–	–	[23]
			8	81.04	69.46	98.14				
			10	80.69	76.81	98.83				
			12	82.19	78.62	99.31				

[a]Reactor type, abbreviations: BNR biological nutrient removal, MBR membrane bioreactor, hybrid MBBR-MBR_{ap} hybrid moving bed biofilm reactor – membrane bioreactor containing carriers in the anaerobic, anoxic and aerobic zones, hybrid MBBR-MBR_{bp} hybrid moving bed biofilm reactor-membrane bioreactor which contained carriers only in the anaerobic and anoxic compartments, UCT–MBR University of Cape Town membrane bioreactor, step-feed pilot scale modified step-feed process, AOA anaerobic/aerobic/anoxic, AAO-BCO anaerobic anoxic oxic-biological contact oxidation.

The average influent and effluent SS concentrations were 264.0±81.0 and 14.9±7.6 mg/dm^3, respectively, while the concentrations of VSS were 201.7±56.2 and 12.2±6.1 mg/dm^3 in the influent and effluent wastewaters, respectively. The removal efficiencies were calculated as 94±4% for SS and 94±4% for VSS. Figures 3f and 3g display the changes of the SS and VSS concentrations measured in the influent and effluent wastewaters, respectively, along with their respective removal efficiencies.

The results of various studies [18–23] are shown in Table 4 and compared with the results from the current study. The removal efficiencies of COD, TN (total nitrogen), NH_4^+-N, TP, PO_4^{3-}-P, and SS in this study matched those presented in literature. Although slightly higher removal efficiencies were observed in some lab-scale studies, more similar performances were obtained in pilot-scale studies [18].

Ten data points other than those used for model training were used as the input values for the fuzzy model to predict the performance of the system. The results of the model and measurement were compared to assess the performance of the model. Figure 4 shows the measured and predicted values for the five fuzzy models along with regression lines and coefficients of determination. In the first model, the input variable was the influent COD. These variables were linked to effluent COD with a fuzzy connection. The coefficient of determination for the first model was 0.892 (Fig. 4a). This result was statistically significant ($p < 0.001$). After the addition of TKN to the input variables (model 2), the coefficient of determination was reduced to 0.883 (Fig. 4b). However, this model had still a high significance level ($p < 0.001$). The results suggested that the fuzzy model can be used confidently to predict the effluent COD concentration with a known influent COD concentration. Although a weaker correlation was observed between the measured and calculated values after integration of the influent TKN into the model, the difference was slight, and it was obvious that models 1 and 2 produce similar results.

Influent TKN was used as the input variable for model 3. The effluent TKN concentration was the output variable. The correlation between the measured and the predicted effluent TKN concentrations was 0.796 ($p < 0.001$) (Fig. 4c). When the influent COD was also integrated into the model as an input variable (model 4), a higher correlation coefficient (0.825) was obtained ($p < 0.001$) (Fig. 4d). The results suggested that although the effluent TKN concentration can be predicted by the fuzzy model with known influent TKN concentration, better results can be obtained if the influent COD concentration is known. In the fifth model, the input variable was influent TP, and the output variable was effluent TP. The correlation coefficient between the measured and predicted effluent TP concentrations was 0.850 ($p < 0.001$) (Fig. 4e). The results suggested that the effluent TP concentration from the modified five-stage Bardenpho process can be predicted confidently by the fuzzy model. Although a number of different models were also established with varying combinations of input and output variables, the first five models with the best prediction performances are presented.

An example use of fuzzy models for estimating the performance of activated sludge systems has been presented by Yang et al. [24]. The effluent COD concentration has been estimated by a fuzzy approach eliminating the need for solving complex nonlinear equations in ASM1. However, Zhu et al. [25] reported that the fuzzy models can confidently be used for estimating nitrogen removal efficiency based on C/N ratios in the influent. In this study, effluent COD, TKN, and TP concentrations were predicted with the correlation of more than 80% according to the influent concentrations.

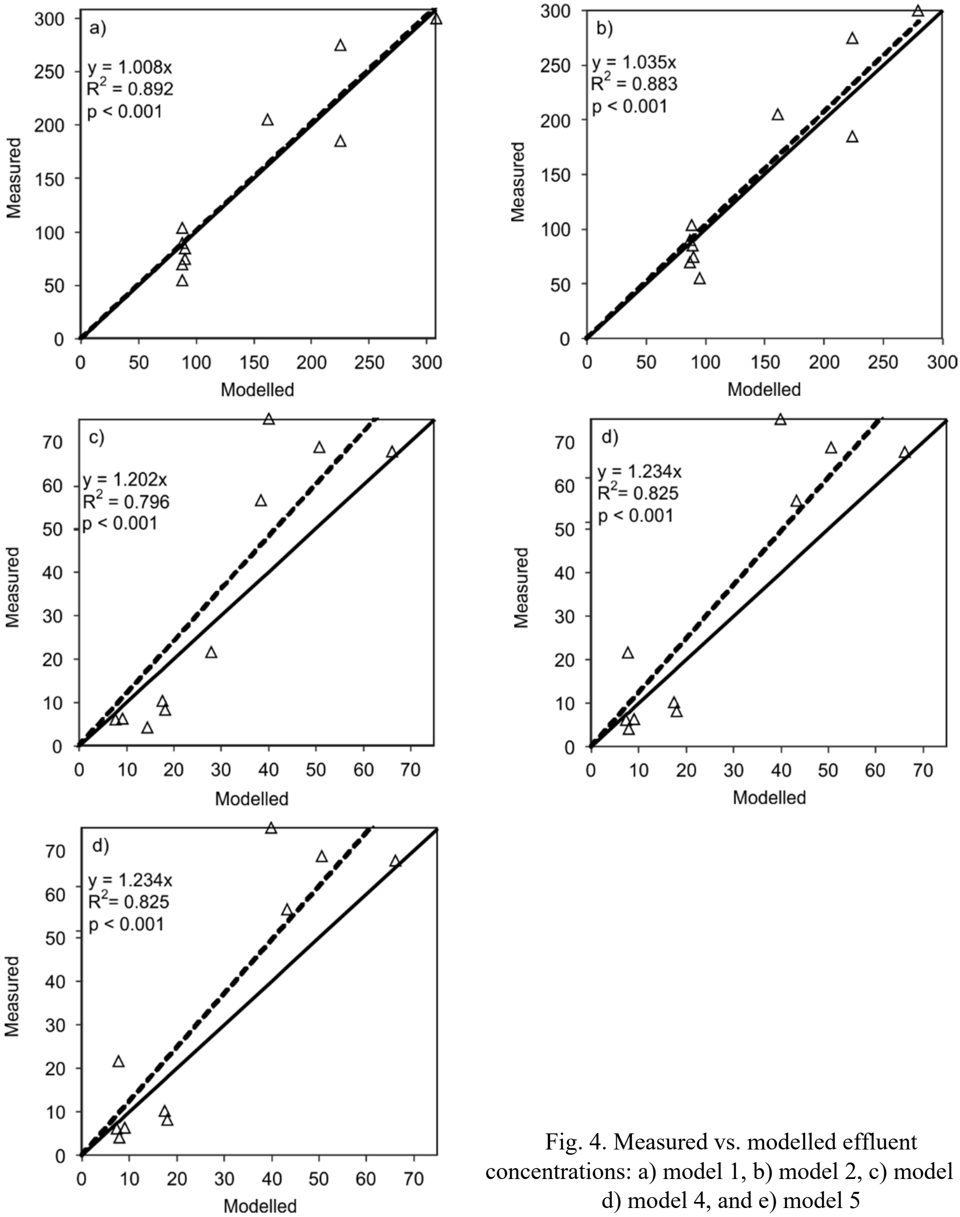

Fig. 4. Measured vs. modelled effluent concentrations: a) model 1, b) model 2, c) model 3, d) model 4, and e) model 5

4. CONCLUSIONS

The modified five-stage Bardenpho process successfully removed C, N, P, and SS with over 85% removal efficiencies. The proposed process can be confidently employed in full-scale applications where improved nitrogen and phosphorus removal are desired.

The fuzzy approach in this study proved useful to predict the effluent COD, TKN, and TP concentrations. The correlation coefficients (greater than 0.80 between the measured and predicted effluent concentrations) showed that the model was also satisfactory in explaining the performance of complex phenomena. The fuzzy model can be used confidently to predict the effluent COD, TKN, and TP concentrations with known influent concentrations.

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