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**Research Article / Araştırma Makalesi**

# MUNICIPAL WASTEWATER TREATMENT WITH A PILOT SCALE TWO-STAGE CASCADE BIOLOGICAL NUTRIENT REMOVAL PROCESS

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## ABSTRACT

In this study, a pilot-scale, two-stage cascade biological nutrient removal (TSC-BNR) process with a 10 $m^3.d^{-1}$ capacity was used in order to remove carbon and nutrient from municipal wastewater. The process was composed of screens, a primary sedimentation tank, a distribution tank, an anaerobic tank, anoxic1/aerobic1/anoxic2/aerobic2 tanks, and a final sedimentation tank. Real (Sewer system) wastewater was fed to the pilot plant and the inflow was fed to the anaerobic and anoxic2 tanks at the same rates to eliminate the need for external carbon source in the second stage anoxic tank. The mixed liquor suspended solids (MLSS) concentration was kept between 4500 and 5500 $mg.L^{-1}$ during the study. The sludge retention time was 15 days and the hydraulic retention time was 16 hours. The average concentrations of chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen ($NH_4^+$-N), total phosphorus (TP), phosphate phosphorus ($PO_4^{3-}$-P), suspended solids (SS), and volatile suspended solids (VSS) in the influent were 555 $mg.L^{-1}$, 71.9 $mg.L^{-1}$, 44.0 $mg.L^{-1}$, 8.1 $mg.L^{-1}$, 4.0 $mg.L^{-1}$, 316 $mg.L^{-1}$, and 230 $mg.L^{-1}$, respectively, the average removal efficiencies were 86.7±10.4%, 80.3±11.0%, 92.5±10.1%, 89.5±6.8%, 87.5±8.8%, 94.8±3.2%, and 95.0±3.4%, respectively. The results indicated that TSC-BNR process can be confidently used for the removal of carbon and nutrients from medium-strength municipal wastewaters.
**Keywords:** Biological nutrient removal, cascade reactor, domestic wastewater.

## PİLOT ÖLÇEKLİ İKİ KADEMELİ KASKAT BİYOLOJİK NUTRİENT GİDERME PROSESİNDE EVSEL ATIKSULARIN ARITILMASI

## ÖZ

Bu çalışmada evsel atıksulardan karbon ve nütrient giderimi için pilot ölçekli ve 10 $m^3.d^{-1}$ kapasiteli iki kademeli kaskat biyolojik nütrient giderme (TSC-BNR) prosesi kullanılmıştır. Proses ızgara, ön çöktürme tankı, dağıtım tankı, anaerobik tank, anoksik1/aerobik1/anoksik2/aerobik2 tankları ve son çöktürme tankından oluşmaktadır. İkinci kademe anoksik tankta harici karbon kaynağı ihtiyacını elimine edebilmek için giriş atıksuyu anaerobik ve anoksik2 tanklarına eşit oranlarda beslenmiştir. Çalışma süresince MLSS (mixed liquor suspended solids) konsantrasyonu 4500-5500 $mg.L^{-1}$ arasında tutulmuştur. Çamur yaşı 15 gün ve hidrolik bekletme süresi 16 saattir. Giriş suyu kimyasal oksijen ihtiyacı (KOİ), toplam azot (TN), amonyum azotu ($NH_4^+$-N), toplam fosfor (TP), fosfat fosforu ($PO_4^{3-}$-P), toplam katı madde (TKM) ve uçucu katı madde (UKM)konsantrasyonları sırasıyla 555 $mg.L^{-1}$, 71,9 $mg.L^{-1}$, 44,0 $mg.L^{-1}$, 8,1 $mg.L^{-1}$, 4,0 $mg.L^{-1}$, 316 $mg.L^{-1}$ ve 230 $mg.L^{-1}$ iken ortalama giderim verimleri sırasıyla %86,7±10,4, %80,3±11,0, %92,5±10,1, %89,5±6,8, %87,5±8,8, %94,8±3,2 ve %95,0±3,4 olarak belirlenmiştir. Sonuçlar iki kademeli kaskat biyolojik nütrient giderme (TSC-BNR) prosesinin orta-kuvvetli evsel atıksulardan karbon ve nütrient gideriminde güvenli bir şekilde kullanılabileceğini göstermiştir.
**Anahtar Sözcükler:** Biyolojik nütrient giderimi, kaskat reaktör, evsel atıksu.

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## 1. INTRODUCTION

Residential and industrial wastewaters from urban region cause several environmental problems such as eutrophication and pollution of surface waters when discharged to the receiving bodies without necessary and enough treatment. For these reasons, wastewaters must be treated before they are discharged to the receiving water bodies. Treatment is the process of reducing the pollutants into less harmful/harmless end products. The process may be accomplished by either physical, chemical, or biological means. Biological nitrification-denitrification [1] or chemical precipitation are employed to remove nutrients from wastewaters. In recent years, biological nutrient removal (BNR) processes have been developed to ensure higher nutrient removal efficiency and to reduce chemicals usage [2]. Several process configurations are employed for this purpose including pre-denitrification (A/O) process, anaerobic/anoxic/aerobic process ($A^2O$), University of Cape Town (UCT), and 5-stage Bardenpho processes [3].

Biological treatment processes offer high efficiencies for nutrient removal when wastewater includes adequate carbon source and high chemical oxygen demand/total nitrogen (COD/TN) ratio [4]. Sometimes, the organic carbon available in wastewater is not sufficient for effective removal of nutrients in enhanced biological wastewater treatment processes. Over years, a great number of process configurations has been developed to enhance nutrient removal efficiencies from wastewaters with low carbon/nitrogen (C/N) ratio [5, 6]. In some of the BNR processes, methanol and acetate is added to the wastewater to meet the carbon requirement in the nitrification-denitrification steps. On the other hand, step-feed biological treatment processes are proposed to ensure high denitrification efficiencies for ammonium-rich or low C/N wastewaters [7]. In this configuration, step-feeding of the influent wastewater replaces the function of methanol addition to the secondary anoxic zone [8]. Step-feeding of the influent wastewater to treatment stages improves nitrogen removal efficiency [9]. The step-feeding process also offers the advantage of reduced costs by eliminating the need for external carbon source. The major advantage of the process is that complete nitrification-denitrification is achieved, while complex operation and the need for feeding the influent to each anoxic zone are the major disadvantages [10]. Besides, researches have shown that step-feeding provides high and stable nutrient removal efficiencies in reduced tank volumes in full-scale applications and that its advantages weigh more than its disadvantages [11, 12]. Related researches have clearly indicated that TN and phosphate removal efficiencies are higher in step-feed process. TN and phosphate removal efficiencies were over 85% and 95%, respectively in a step-feed $A^2O$ process. TN removal efficiencies were higher by 13.2% compared to the conventional $A^2O$ process when step-feed is not applied for wastewater with C/N ratios between 3.6-3.8 [13].

In this study, a pilot-scale two-stage cascade biological nutrient removal process (TSC-BNR) having a volume of 8.6 $m^3$ with an installed capacity of 10 $m^3.d^{-1}$ was used. The pilot plant is located within ISKI (Istanbul Water and Sewerage Administration) Ataköy Biological Wastewater Treatment Plant site. During the operation, the influent was divided equally between the bio-P (anaerobic, 5 $m^3.d^{-1}$) and denitrification2 (anoxic, 5 $m^3.d^{-1}$) tanks, and evaluated the performance of TSC-BNR process during the domestic wastewater treatment.

## 2. MATERIALSAND METHODS

### 2.1. Two-Stage Cascade Biological Nutrient Removal (TSC-BNR) Process

The pilot-scale two-stage cascade biological nutrient removal process (TSC-BNR), used in this study, was installed in Ataköy Biological Wastewater Treatment Plant of the Istanbul Water and Sewerage Administration (Istanbul/Turkey). Pilot scale process had a total volume of 8.6 $m^3$. Sewer wastewater from the effluent of grit removal unit of the full-scale plant was used in the study. The reactor with two feedlines was used as shown in Fig. 1. The return activated sludge

(RAS), two internal recycle (IR) lines ratios were also shown in Fig. 1. Two internal recycle (IR) lines were responsible of returning the nitrate from aerobic1 to anoxic1 (IR1), and from aerobic2 to anoxic2 (IR2). The effluent of distribution tank was divided into two parts: one part flowing into the anaerobic tank and the rest by-passing to the secondary anoxic tank directly with a ratio defined as distribution ratio in this study for good use of carbon substrates for denitrification in anoxic unit. The influent flow rate was 10 $m^3.d^{-1}$ and the influent distribution ratio was 50:50%. Several mechanical stirrers were equipped in distribution, anaerobic, anoxic1, and anoxic2 tanks separately to ensure complete mixing of sludge and wastewater. Four sets of fine bubble air diffusers were installed at the bottom of two aerobic tanks to supply oxygen. The hydraulic retention time for biological stage volume was around 16 h, the sludge retention time was 15 days and the average mixed liquor suspended solid (MLSS) concentration was in the range of 4500–5500 $mg.L^{-1}$. The process was inoculated with the sludge from the RAS line of the full-scale plant.

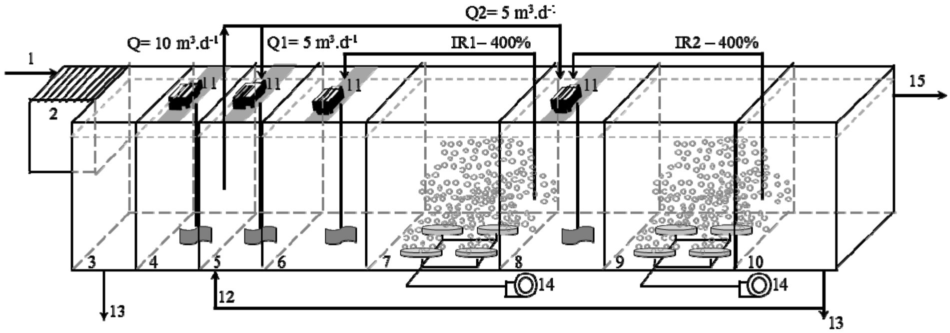


**Figure 1.** Schematic diagrams of the pilot-scale two-stage cascade biological nutrient removal process (TSC-BNR); (1) influent; (2) screen; (3) primary settling– 0.25$m^3$; (4) distribution tank– 0.25$m^3$; (5) anaerobic– 0.5$m^3$; (6) anoxic1– 1.4$m^3$; (7) aerobic1– 1.7$m^3$; (8) anoxic2– 1.4$m^3$; (9) aerobic2– 1.7$m^3$; (10) secondary settling– 1.4$m^3$; (11) stirrer; (12) return activated sludge – 80%; (13) waste sludge; (14) blower; (15) effluent.

### 2.2. Analytical Methods

Two samples per week were collected from the influent, effluent and each step of the pilot-scale reactor. These samples were analyzed for COD (chemical oxygen demand), $NH_4^+$-N (ammonium nitrogen), $NO_3$-N (nitrate nitrogen), $NO_2$-N (nitrite nitrogen), TP (total phosphorus), $PO_4^{3-}$-P (phosphate phosphorus), SS (suspended solids), and VSS (volatile suspended solids). Standard Methods [14] were employed for the analyses. COD was measured using the open reflux method (5220-B). The $NH_4^+$–N and TKN measurements were conducted according to methods 4500-$NH_4^+$-C and 4500-Norg-B, 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. SS concentration was determined according to Standard Method 2540-D. Each analysis was performed in three replicates. Samples were collected from the effluents of stages and collected samples, except influent and effluent samples from the pilot-scale plant, were settled for a duration of 1 h to ensure sufficient MLSS settling. Pilot-scale reactor was operated for a period of 14 weeks. Analyses of the samples showed that removal efficiencies increased gradually and that the process reached steady-state after 4 weeks. The pH and temperature of influent wastewater were 7.57±0.19, and 24.3±1.9ºC, respectively. The flowrate of the blowers were approximately 1.9 $m^3.min^{-1}$ to keep dissolved oxygen concentrations in the aerobic stages between 2.0 and 2.5 mg.$L^{-1}$. The stirring motors were run at about 350 rpm in distribution, anaerobic tanks, and anoxic tanks.

## 3. RESULTS AND DISCUSSION

### 3.1. Two-Stage Cascade Biological Nutrient Removal Process(TSC-BNR)

Influent and effluent concentrations as well as removal efficiencies in the pilot-scale plant were previously published in [15] and are given in Table 1. COD, $NH_4^+$-N, SS, and TP concentrations for medium-strength and high-strength wastewaters are reported as 430 and 800 mg.$L^{-1}$, 25 and 45 mg.$L^{-1}$, 210 and 400 mg.$L^{-1}$, 160 and 315 mg.$L^{-1}$, 7 and 12 mg.$L^{-1}$, and 5 and 8 mg.$L^{-1}$, respectively [16]. Considering the influent wastewater characteristics, the real municipal wastewater used in this study falls under the category of medium-strength wastewaters.

**Table 1.** Influent and effluent concentrations as well as removal efficiencies in pilot-scale treatment plant

| | Influent (mg.$L^{-1}$) | Effluent (mg.$L^{-1}$) | Removal efficiency (%) |
|---|---|---|---|
| COD | 555± 60.1 | 75 ± 60.7 | 86.7 ± 10.4 |
| $NH_4^+$-N | 44 ± 6.7 | 3.1 ± 3.7 | 92.5 ± 10.1 |
| $NO_2^-$-N | 0.03 ± 0.02 | 0.55 ± 0.21 | - |
| $NO_3^-$-N | 0.06 ± 0.04 | 2.08 ± 0.59 | - |
| TP | 8.1 ± 0.4 | 0.9 ± 0.6 | 89.5 ± 6.8 |
| $PO_4^{3-}$-P | 4 ± 0.5 | 0.5 ± 0.4 | 87.5 ± 8.8 |
| SS | 316 ± 47 | 15.9 ± 8.1 | 95.0 ± 3.2 |
| VSS | 230 ± 33 | 10.9 ± 5.9 | 95.0 ± 3.4 |

Average value in 20 samples
Standard deviation from 20 data points

Changes of parameters for each step of the process are shown in Fig. 2. In Figure 2, COD concentrations show a clear decreasing trend in each step. A significant reduction of COD concentration took place within the anaerobic zone. The reason for this was the dilution of influent wastewater with recycled sludge, which is dilute in COD concentrations. The rate of COD oxidation was higher in anoxic1 zone than aerobic1 zone because of heterotrophic bacteria using nitrate as the electron acceptor. When concentration of electron acceptor is high enough, the rate of COD oxidation is controlled by its concentration. Since COD concentration is high in anoxic1 zone with respect to the aerobic1 zone, it is expected that COD oxidation takes place faster in anoxic1 zone. On the other hand, since half of the influent was fed to anoxic2 tank, COD oxidation rate was lower in anoxic2 tank than it was in aerobic2 tank due to the limiting concentrations of electron acceptor within the former one. This means, in contrast to conventional 5-stage Bardenpho process, that the aerobic2 tank is not only for purging nitrogen gas prior to final sedimentation, but also COD oxidation to a certain degree was achieved in this step.

$PO_4^{3-}$-P concentrations increased in the anaerobic tank due to phosphate accumulating organisms (PAOs) released ortho-phosphate (Fig. 2). Besides, TP concentrations showed a drastic increase in this step. The reason for this was the return activated sludge. Normally, TP concentrations in an anaerobic zone could be increased due to release of $PO_4^{3-}$-P by PAOs. However, interference from bacterial mass could also have contributed to this drastic increase in TP concentrations since measurements were performed in settled sample and TP concentrations include phosphorus in particulate form. From this point forward, both $PO_4^{3-}$-P and TP concentrations decreased gradually. The rate of change in $PO_4^{3-}$-P was sharper in aerobic1 tank due to the fact that most of the PAOs are strictly aerobic with a smaller fraction of facultative aerobic PAOs. The reason for the similar trend in $PO_4^{3-}$-P concentrations in anoxic2 and aerobic2 tanks is the same. In Figure 2, it is obvious that the rate of change in TP concentration (the slope of TP line) was slightly reduced in anoxic2 tank compared to the rate of change in the anoxic1 tank. The main reason for this is that half of the influent wastewater was fed to the anoxic2 tank and organic fraction of phosphorus was higher in influent wastewater.

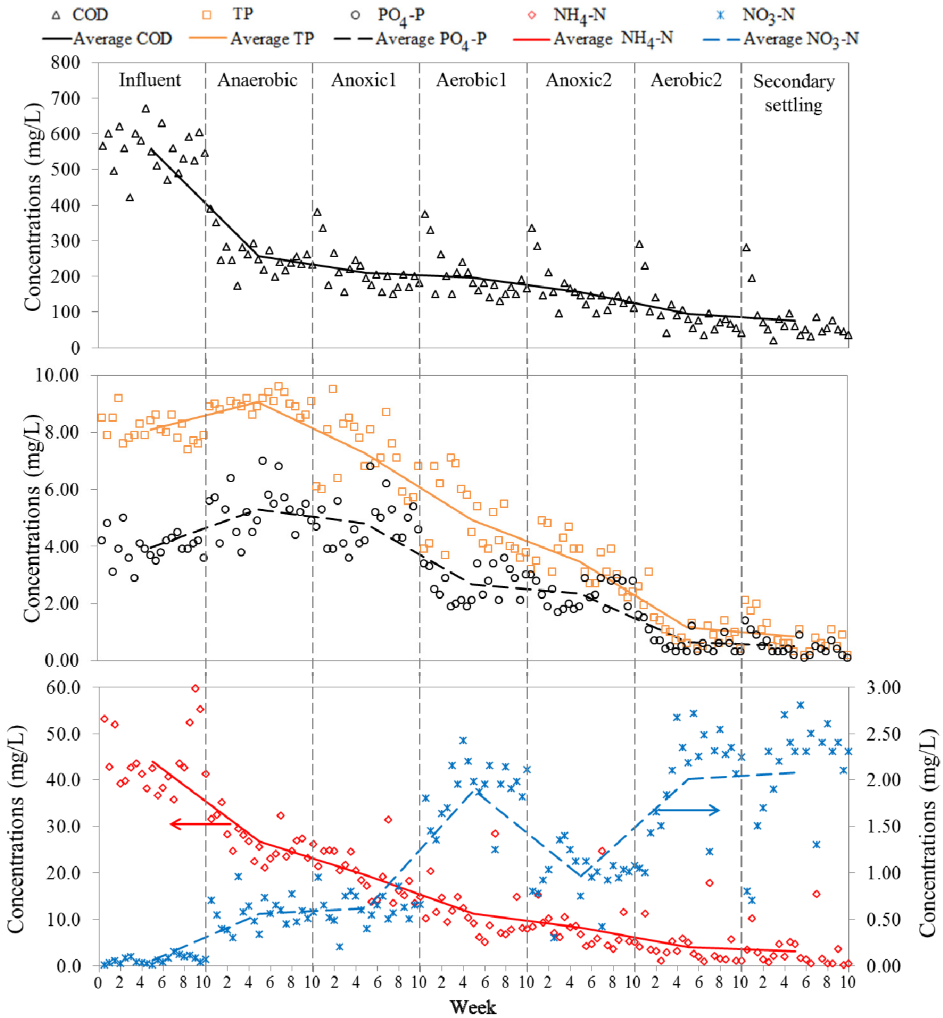


**Figure 2.** Changes of parameters each step of two-stage cascade biological nutrient removal process (TSC-BNR)

$NH_4^+$-N concentrations showed a continuous decrease similar to COD concentrations. The main reason for the decrease in anaerobic tank was due to dilution of the influent wastewater with return activated sludge. The increase in $NO_3^-$-N concentrations in anaerobic tank was that return activated sludge with high $NO_3^-$-N content was mixed with influent wastewater in this tank, too. In anoxic1 tank, the concentrations increased slightly due to mixing with high nitrate concentrations in internal recycle flow. $NH_4^+$-N concentrations decreased gradually in all steps with slower rate of change in anoxic2 tank since part of influent was fed to this tank. On the other hand, $NO_3^-$-N concentrations were increased in both aerobic tanks as a result of actions of nitrifying bacteria. Lower concentrations of $NO_3^-$-N were observed in anoxic tanks. In anoxic2 tank, the sharp decrease was mainly due to mixing with influent wastewater. Average concentrations of COD, $NH_4^+$-N, TKN, $PO_4^{3-}$-P, and $NO_3^-$-N from each step are shown in Table 2.

**Table 2.** Changes of effluent concentrations each step of the process [17]

| | Effluent concentrations (mg/L) | | | | |
|---|---|---|---|---|---|
| | **Anaerobic ($0.5\ m^3$)** | **Anoxic1 ($1.4\ m^3$)** | **Aerobic1 ($1.7\ m^3$)** | **Anoxic2 ($1.4\ m^3$)** | **Aerobic2 ($1.7\ m^3$)** |
| **COD** | 256.6 ± 48.6 | 211.0 ± 58.9 | 195.8 ± 63.4 | 156.3 ± 60.0 | 95.3 ± 63.4 |
| **$NH_4^+$-N** | 26.8 ± 3.8 | 19.4 ± 4.9 | 11.3 ± 5.5 | 8.3 ± 4.8 | 4.0 ± 4.1 |
| **TKN** | 40.5 ± 12.5 | 32.5 ± 14.5 | 22.3 ± 13.5 | 19.6 ± 12.7 | 13.5 ± 9.7 |
| **$PO_4^{3-}$-P** | 5.3 ± 0.8 | 4.8 ± 0.8 | 2.7 ± 0.6 | 2.4 ± 0.5 | 0.7 ± 0.4 |
| **$NO_3^-$-N** | 0.56 ± 0.16 | 0.62 ± 0.17 | 1.89 ± 0.30 | 0.96 ± 0.27 | 2.01 ± 0.53 |

### 3.2. Correlation Analysis

A correlation analysis was also performed to assess the relationship between removal efficiencies for seven performance parameters. The correlation plots are given in Fig. 3. The results showed that satisfactorily higher correlation coefficients exist between removal efficiencies for seven parameters.

The highest correlation coefficient was calculated as 0.950 between SS and VSS removal efficiencies, which is an expected result since both parameters measure the sludge settling properties in the final sedimentation tank. The correlation coefficient between removal efficiencies for $PO_4^{3-}$-P and TP ranked second (0.902) explaining the relationship between satisfactory activity of phosphorus accumulating organisms and good sludge settling properties under steady-state conditions. On the other hand, the COD removal efficiencies were in good agreement with removal efficiencies for $PO_4^{3-}$-P, TP, SS, and VSS with correlation coefficients ranging from 0.686 to 0.737. Negative correlations were observed between $NH_4^+$-N removal efficiencies and SS and VSS removal efficiencies.

Table 3 shows the comparison of results of this study with previous works related with processes for the treatment of municipal and synthetic wastewaters. Table 3 clearly shows that the removal efficiencies and examined parameters obtained in TSC-BNR process was satisfactory compared to similar processes for organic material and nutrient removal from wastewaters.

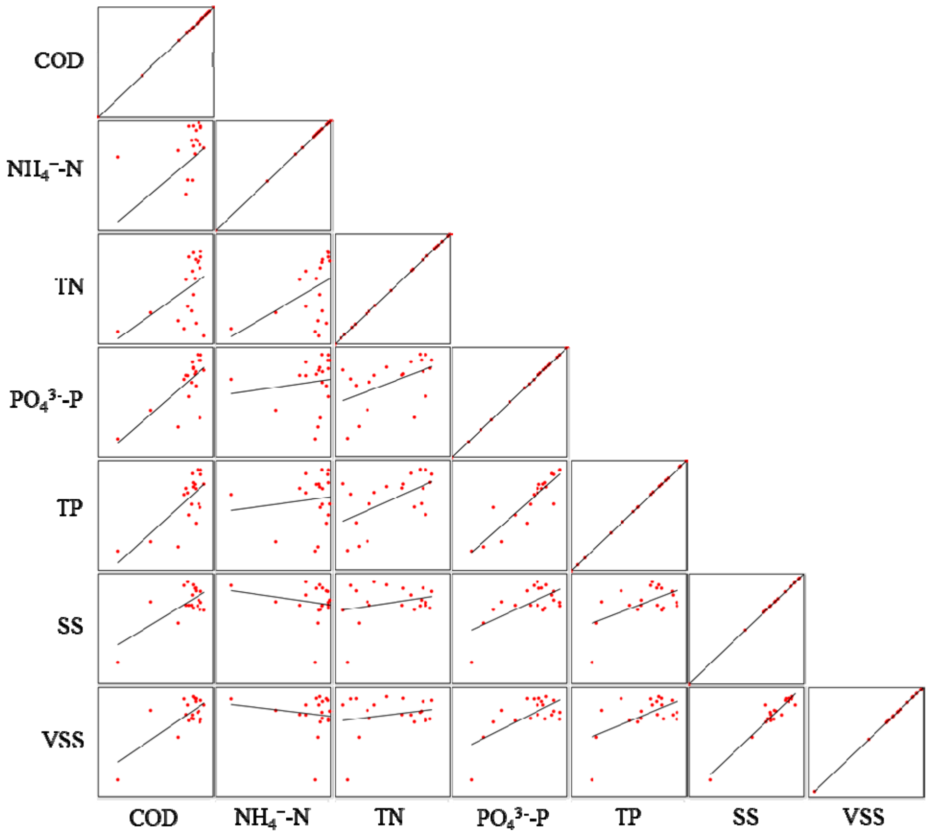


**Figure 3.** Correlation plots for seven performance parameters

**Table 3.** Comparison of results from two-stage cascade biological nutrient removal process (TSC-BNR) with literature data (adapted from Manav-Demir [17])

| Reactor type | Wastewater | V ($m^3$) | Removal efficiency (%) | | | | | | | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **COD** | **TP** | **$PO_4^{3-}$-P** | **$NH_4^+$-N** | **TN** | **SS** | **VSS** | |
| This study | Municipal | 8.6 | 86.7 | 89.5 | 87.5 | 92.5 | 80.3 | 94.8 | 95.0 | [17] |
| MFSF | Municipal | 0.067 | 78.9 | 86.11 | - | 98.31 | 70.24 | - | - | [11] |
| Cascade UCT | Municipal | 0.34 | 81.9 | - | 63.6 | 85.3 | - | - | - | [4] |
| 5-stage BNR | Municipal | 16.2 | 87.0 | 87.0 | - | - | 79.0 | - | - | [18] |
| VSMBR | Municipal | 1333 L | 96.0 | 78.0 | - | - | 74.0 | 100 | - | [19] |
| Modified A2O | Municipal | 1871 | 86.6 | 89.8 | - | 98.0 | 73.6 | 50.4 | - | [20] |
| BNR | Municipal | 1.7 | 89.0 | 95.0 | - | - | 76.0 | - | - | [21] |
| 5-stage BNR | Municipal | 16.2 | 87.0 | - | 87.0 | 88.0 | 79.0 | 90.0 | - | [22] |
| SBR | Synthetic | 68 L | 94.0 | - | 65.0 | - | 86.0 | - | - | [23] |
| AOA | Synthetic | 43L | - | - | 87.3 | 93.0 | 70.3 | - | - | [24] |
| SAM | Synthetic | 8 L | 99.2 | 79.1 | 79.8 | 99.5 | 74.2 | - | - | [25] |
| SBR | Municipal | 0.166 | 85.3 | 85.1 | - | 98.6 | 80.5 | - | - | [26] |
| A2O-MBR | Municipal | 0.385 | 95.5 | 48.6 | - | - | 84.6 | - | - | [27] |
| AAA | Municipal | 10 L | 85 | - | - | 85.4 | - | - | - | [28] |

MSFS: Modified four step-feed reactor; UCT: University of Cape Town; BNR: Biological nutrient removal; VSMBR: Vertical submerged membrane bioreactor; A2O: Anaerobic–anoxic–oxic; SBR: Sequencing batch reactor; AOA: Anaerobic–aerobic–anoxic; SAM: Sequencing anoxic/anaerobic-aerobic membrane bioreactor; A2O-MBR: Anaerobic-anoxic-oxic membrane bioreactor; AAA: Alternating aerobic-anoxic process

## 4. CONCLUSIONS

At the two stage cascade biological nutrient removal (TSC-BNR) process, average COD, TKN, $NH_4$-N, TP, $PO_4^{3-}$-P, TSS, and VSS removal efficiencies were 86.7±10.4%; 84.0±11.7%; 92.5±10.1%; 89.5±6.8%; 87.5±8.8%; 94.8±3.2%, and 95.0±3.4% respectively. Embedding two anoxic tanks into the process provided higher removal efficiencies and safe operation. The influent wastewater was fed to anaerobic and anoxic2 tanks to provide required organic substrate for phosphate release. The influent wastewater, which is the influent of İSKİ Ataköy Advanced Biological Wastewater Treatment Plant, was classified as medium-strong when compared to wastewater characterization in current literature. The results of the study clearly showed that satisfactory treatment efficiencies were achieved by TSC-BNR process and the process can confidently be used for treating wastewaters with similar wastewater characteristics.

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