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# Assessment of seasonal variations on the performance of P-UASB/BAF for municipal wastewater treatment

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ABSTRACT

In this study, the effect of seasonal variations on the performance of combined anaerobic–aerobic system for wastewater treatment was investigated. The pilot plant system consists of packed bed anaerobic sludge blanket, followed by a biological aerated filter. The packing material in both units was a non-woven polyester fabric. The system was operated for more than two years at ambient temperature. The results indicated that the performance of the pilot plant was very satisfactory during the whole seasons. However, in summer, slightly better results were achieved for chemical oxygen demand, biological oxygen demand, total suspended solids and total Kjeldahl nitrogen due to the increase in temperature. Their corresponding average removal values were 90, 91, 97, and 54%, respectively, compared with 88, 90, 91, and 46% in winter. Nitrogen removal was related to nitrification/denitrification and bacterial assimilation, where its activity increased in the summer. The quality of the treated effluent during the whole seasons complies with the National Regulatory Standards for reuse in irrigation.

*Keywords:* Sewage; Treatment; Up-flow anaerobic sludge blanket (UASB); Biological aerated filter (BAF); Packing material

## 1. Introduction

Anaerobic treatment of domestic wastewater, especially with the up-flow anaerobic sludge blanket (UASB) reactors, has many advantages such as low sludge production, operational simplicity, and low operation costs [1,2]. Generally, anaerobic treatment is practiced to break down biodegradable substances and to reduce the overall organic load, particularly from wastewater. However, it partially treats the wastewater and the effluent still contains organic matters, suspended solids and nutrients [2]. In order to obtain better process, stability, and performance efficiency, posttreatment is required [3,4]. Some studies have focused on the combinations of anaerobic and aerobic processes for the treatment of municipal, industrial, and agricultural effluents [5], for example anaerobic filter-activated sludge system, UASB-attached aerobic filter [6], aerobic baffled reactor–activated sludge

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system [7] aerobic–anaerobic filters [8] and packed bed anaerobic-multistage sand filtration [1].

Among the aerobic treatment systems is the biological aerated filter (BAF). It is a promising bioreactor for wastewater treatment and reuse [9]. BAF is a novel, flexible, and effective bioreactor that provides a small footprint process option at various stages of wastewater treatment [10]. BAFs usually treat settled sewage, removing biochemical oxygen demand (BOD), suspended solids, and ammonia [11]. BAFs are fixed-film reactors that use media with a high specific surface area for wastewater treatment [12] and can be used at various stages of wastewater treatment [13]. As the application of BAF increases, deeper understanding of operational discipline, operation optimization, and structural characteristics of BAF is required to improve the treatment efficiency and operation stability. Moreover, biological wastewater treatment is affected by changes in the environmental conditions to which the biomass are exposed such as dissolved oxygen (DO), pH, and temperature [14]. Wastewater temperature has an effect on both sedimentation and biological treatment processes. Temperature influences the rate at which biological oxidation occurs [15]. In the submerged bioreactors, the removal of organic matters is performed by a microbial film on the surface of the filter media; it has been known that the amount of film accumulating in the filter fluctuates seasonally and the amount of film increased in winter and decreased in summer [16]. There are few studies about the effect of temperature shifts on aerobic biological wastewater treatment, most of which come from temperature adjustments in steady-state studies. In this study, the effect of temperature changes on the performance of an anaerobic–aerobic system for wastewater treatment during different seasons was thoroughly investigated. The treatment system used is a pilot scale packed bed up-flow anaerobic sludge blanket (P-UASB) followed by BAF. Both reactors are packed with a non-woven polyester fabric (NWPF) which act as bioholder and it is used for the first time for this purpose.

## 2. Materials and methods

### 2.1. Description of the combined anaerobic–aerobic system

The anaerobic–aerobic pilot plant treatment system composes of a packed bed up-flow anaerobic sludge blanket followed by a BAF then inclined plate settler (IPS). A schematic diagram of the treatment train is shown in Fig. 1.

Both UASB and BAF were packed with a NWPF with different geometric configurations. This material is used for the first time in both reactors [3]. The system was located in a nearby wastewater treatment plant (WWTP), North Cairo, and fed continuously with primary treated sewage. It was operated for almost 2 years at ambient temperature ranged from 10–40°C.

#### 2.1.1. Description of P-UASB

A packed bed UASB was used as a basic unit for treating the prescreened sewage. It was designed based on a total flow of 10 $m^3/d$ and a retention time of 6 h. The effective unit volume is 2.2 $m^3$ with an internal dimension of 120 cm × 120 cm and a height of 240 cm. The reactor was packed with rolled NWPF framed in a polyethylene cylindrical shape and located at 60 cm apart from the bottom of the reactor. The height of the packing material was 30 cm and it was confined in a plastic basket. The reactor was provided with the piping arrangement of influent and effluent wastewater, wastewater sampling points, drainage pipe, and sludge sampling points at different distances along the reactor height. The reactor was seeded with digested sludge collected from a secondary WWTP. The sludge loading rate (SLR) was calculated to be 0.1 kg COD/kg/d and volumetric organic loading rate (OLR) was 1.54 kg COD/$m^3$/d, while the up-flow velocity was 0.25 m/h.

#### 2.1.2. Description of BAF reactor and IPS

The BAF unit was fixed after P-UASB as a post-treatment step. The BAF reactor was designed and fabricated using PVC material. Its internal dimensions were 93 × 78 cm and the overall height was 130 cm. The effective volume was calculated to be 0.94 $m^3$. Five sampling points were placed every 20 cm along the filter bed height starting from the bottom of the filter unit. The effluent from P-UASB was fed to the bottom of BAF and distributed through a PVC network pipes. Two shapes of the NWPF packing material were fixed at a distance of 10 cm from the bottom of the reactor. The NWPF was arranged in vertical plates (12 plates) at a distance of 5 cm apart from each other. The void spaces between every two successive plates were filled with rolled NWPF to increase the surface area for the microorganism's propagation. Oxygen was supplied using compressed air through the bottom of the filter bed with a flow rate of 5 L/min using coiled plastic tubes with very tiny holes. This flow rate was selected to maintain an average DO concentration in the effluent >4 mg/L. The IPS was designed and fabricated using PVC material. The effective volume of the IPS was 0.54 $m^3$, with internal dimensions of

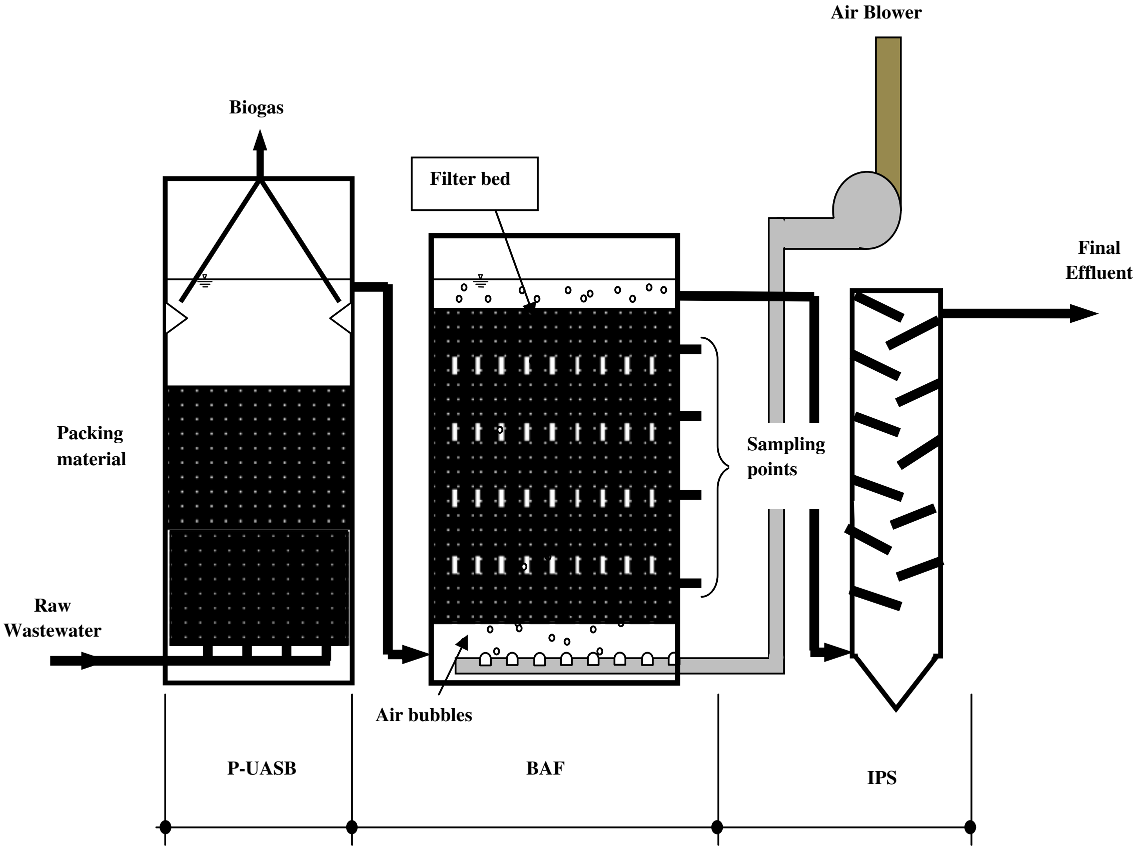

Fig. 1. Schematic diagram of the pilot plant treatment train.

60 × 60 cm and a height of 150 cm. The IPS was provided with inclined plates with an inclination angle of 60° in both directions. The clearance between the two sequential inclined plates was 10 cm.

## 2.2. *Sampling*

Wastewater samples were collected on a weekly basis from the inlet and outlet of P-UASB, BAF, and IPS. The collected samples were preserved in an ice-box at a temperature of 4°C and transferred directly to the laboratory for analysis on the same day. Analyses of the samples were carried out for a duration of more than one year in order to cover the temperature changes during the whole year.

## 2.3. *Physico–chemical and biological analysis*

Physico–chemical and biological analyses were carried out for raw and treated wastewater. The Physico–chemical analysis covered pH, chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonia-nitrogen (N-$NH_4$), nitrite-nitrogen ($NO_2^-$), nitrate-nitrogen ($NO_3^-$), and total phosphate (T.P). The biological parameters covered total coliform and fecal coliform. PH was measured using Jenway pH meter 3510, while COD, $NO_2^-$, $NO_3^-$, and T.P were measured using a spectrophotometer, Lovibond Spectro Direct 712005. Analysis of N-$NH_4$ and TKN were carried out using Gerhardt digestion and distillation apparatus, Vapodest 10sn. Analyses of heavy metals were carried out using Atomic Absorption Spectrometer, Spectra AA 220. All the analyses, unless specified, were carried out according to Standard Methods for the Examination of Water and Wastewater APHA [17].

## 2.4. *Statistical analysis*

Statistical analysis of the collected data was carried out using Microsoft Excel 2010 version. The percentage removal was calculated according to the following equation:

$$\%R = \frac{(C_i \times Q_i) - (C_e \times Q_e)}{C_i \times Q_i} \times 100$$

where $C_i$ = Influent concentration in kg/m$^3$, $C_e$ = Effluent concentration in kg/m$^3$, $Q_i$ = Inflow in m$^3$/d, $Q_e$ = Outflow in m$^3$/d.

## 3. Results and discussions

### 3.1. Raw wastewater characterization

The average characterization of the influent wastewater to the treatment system during the seasonal variations is shown in Table 1. The results show that the average concentrations of total COD and soluble COD were varied along the year. The winter season showed the highest concentration of TCOD, in which its maximum concentration reached 730 mgO$_2$/l. In addition, the average values of BOD and TSS were higher in winter compared with other seasons. This is attributed to the low consumption of water in winter season. Average total coliform and fecal coliform counts were six logs in all seasons. However, slight decrease was noticed in winter season due to lower temperature compared to the summer season and hence the decrease of the propagation of microorganisms.

### 3.2. Effect of seasonal variations on the efficiency of the treatment system

Egypt days are commonly varied between warm and hot, while nights are cool. Egypt has only two seasons: a mild winter from November to April where the temperature ranges between 5 and 20°C and a hot summer from May to October (30–42°C). The only differences between the seasons are variations in daytime temperatures and changes in prevailing winds. Temperatures vary widely in the inland desert areas, especially in summer, when they may range from 7°C at night to 43°C during the day. During winter, temperatures in the desert fluctuate less dramatically, but they can be as low as 0°C at night and as high as 18°C during the day. A phenomenon of Egypt's climate is the hot spring wind that blows across the country. Accordingly, it was worth doing to study the effect of temperature changes on the performance of the integrated pilot plant treatment system.

#### 3.2.1. Removal of COD, BOD, and TSS

The effect of temperature on the treatment efficiency as presented by the residual concentrations of COD, BOD, and TSS from the different treatment units is depicted in Figs. 2(a), (b), and (c)). The results indicated that their corresponding percentage removal values from the P-UASB reactor were ranged between 56 and 63%, 48 and 68%, and 63 and 79%, respectively. Also, it was noticed that the residual values of different pollutants were higher in winter compared with other seasons due to the higher OLR in winter (1.78 kg BOD/m$^3$ d). However, posttreatment using BAF reactor was very efficient. The results indicated that the highest removal values of pollutants were achieved in summer compared with other seasons. The removal rate in summer for COD, BOD, and TSS reached 89, 90, and 91%, respectively, with corresponding average residual values of 41.7 ± 9 mg/l, 22 ± 4 mg/l, and 16 ± 5 mg/l. In spite of the decrease in temperature in winter (5–20°C), the performance of the integrated treatment system was slightly affected. The residual values of COD, BOD, and TSS were slightly higher than those in summer. They were 50.1 ± 10 mg/l, 24 ± 6 mg/l and 30 ± 10 mg/l. The high removal rate in summer can be explained that the increase in temperature up to (40°C) enhanced the activity of aerobic bacteria. The removal of organic

Table 1
Characteristics of raw wastewater during different seasons

| Parameters | Unit | Spring | Summer | Fall | Winter |
|---|---|---|---|---|---|
| Temperature | °C | 25–33 | 32–40 | 22–28 | 9–21 |
| pH-value | – | 7.2–7.5 | 6.7–7.6 | 6.7–7.2 | 6.7–7.1 |
| COD | mg O$_2$/l | 295- 479 | 300–441 | 305–392 | 390–730 |
| BOD | mg O$_2$/l | 170–270 | 180–245 | 112–180 | 146–324 |
| Ammonia | mg/l | 14–27 | 13–38 | 19–27 | 13–29 |
| TKN | mg/l | 19–39.50 | 33–56 | 33–65 | 19–53 |
| Nitrite | mg/l | 0.005–0.03 | 0.008-.031 | 0.005–0.064 | 0.001-.018 |
| Nitrate | mg/l | 0.02–0.57 | 0.06–0.21 | 0.02–0.20 | 0.01–0.50 |
| T.P | mg/l | 1.8–6.0 | 2.5–5.0 | 1.6–5.30 | 2.2–60 |
| Total coliform | MPN/100 ml | $2.50 \times 10^6$ | $3.80 \times 10^6$ | $4.37 \times 10^6$ | $3.15 \times 10^6$ |
| Fecal coliform | MPN/100 ml | $1.85 \times 10^6$ | $3.00 \times 10^6$ | $9.93 \times 10^5$ | $1.13 \times 10^6$ |

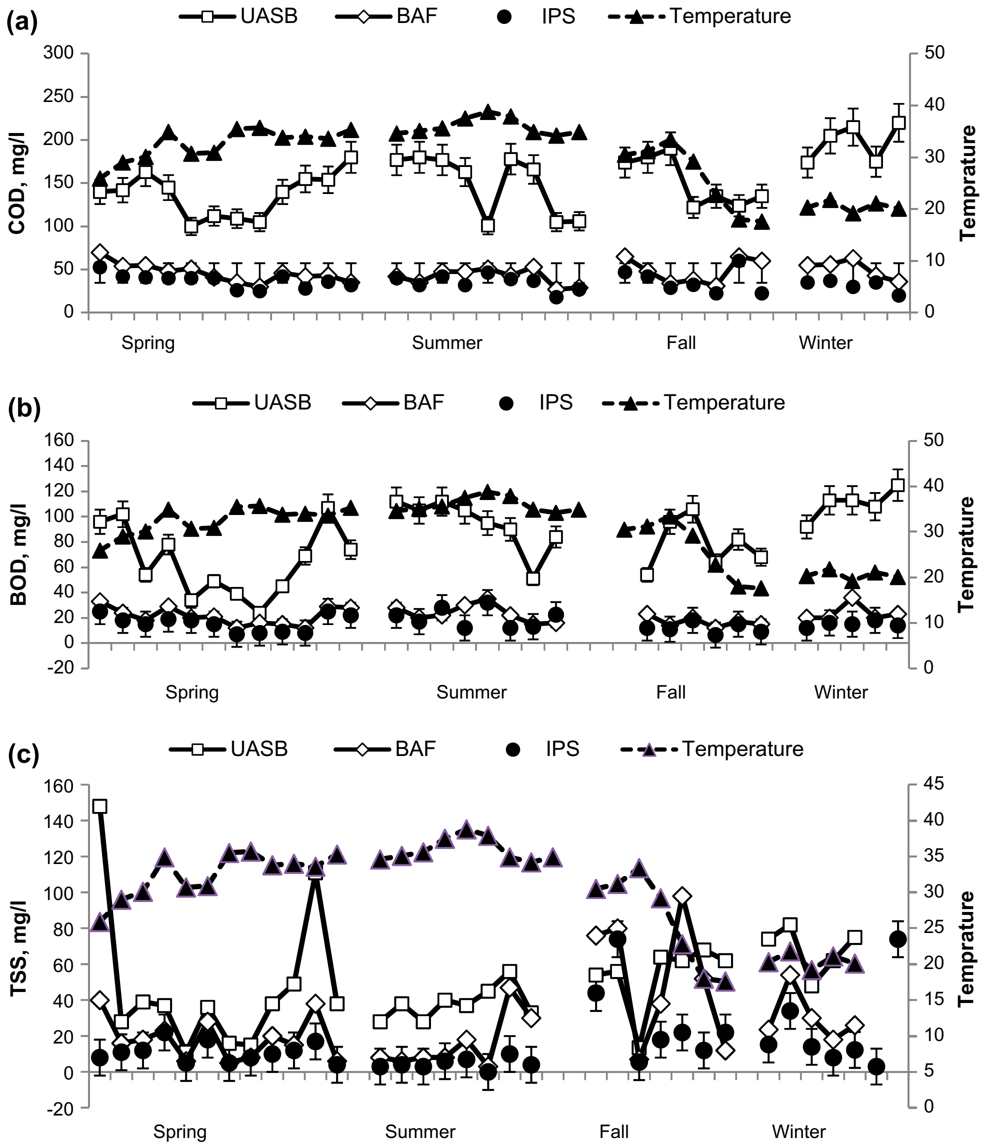

Fig. 2. Effect of temperature on the residual concentrations of (a) COD, (b) BOD, (c) TSS during different seasons.

matters and suspended solids in BAF were achieved by biological oxidation and physical filtration. The high or low removal efficiency was mainly dependent on the accumulation of activated biological film in the filter media bed and mass transfer efficiency. The activity of biofilm attached to the filter media depends on the temperature, and the media morphological characteristics. In addition, it relates to the porosity of the filter bed. The treatment performance decreases with a decrease in temperature [18]. Our results also showed that the effluent from BAF unit still has some residual concentration of suspended particles which require settling. The use of IPS unit produced a very high quality effluent during the whole seasons of the year. However, the removal rate in summer was slightly better than other seasons, especially for physicalchemical parameters. The overall removal efficiency of the treatment system was very high and produced a very high quality effluent. The removal values of COD, BOD, and TSS in summer reached 90, 91, and 97% with average residual values of 34.8 ± 8 mg/l, 23.9 ± 8 mg/l, and 5 ± 1 mg/l, respectively. The high removal rate in the final settler could also be attributed to the complete particulate retention of suspended COD and BOD, high-molecular-weight organics and biomass [19].

### 3.2.2. Nutrients removal

As reported by several authors little or no nutrients removal may be expected in an anaerobic system treating domestic wastewater [20,21]. This was confirmed in our study where the concentrations of ammonia, TKN, and phosphorus in P-UASB effluent were slightly increased. The average concentrations of TKN, ammonia, and phosphorus in the P-UASB effluent during the study period were 34 ± 3 mg/l, 26.4 ± 5 mg/l, and 4.4 ± 1 mg/l, respectively, compared with 32.6 ± 4 mg/l, 23.8 ± 3 mg/l, and 3.1 ± 1 mg/l in raw wastewater. The reason of the low nutrient removal is that during the anaerobic process, organic nitrogen and phosphorous are hydrolyzed to ammonia and phosphate, which are not removed from the system and in consequence, their concentration increases in the liquid phase [22]. Applying the BAF reactor after P-UASB achieved high removal rates of nutrients. The results in Fig. 3 showed that the highest removal efficiency was achieved in summer season due to the increase in temperature, which enhances the activity of nitrifying bacteria and consequently oxidize TKN and ammonia. The average residual values of TKN, ammonia, and T.P were 17.6 ± 2, 12.3 ± 3, and 1.1 ± 1 mg/l, while in winter they reached 20.3 ± 3, 15.2 ± 2, and 1.5 ± 1 mg/l, respectively.

The effect of temperature on nutrients removal was obvious in nitrification and denitrification process. Nitrification is a biological oxidation of ammonia-nitrogen, which consists of two steps, where $NH_4$-N in the presence of oxygen, is first converted to nitrite-nitrogen ($NO_2$-N) by the strictly chemolithotrophic *Nitrosomonas*, *Nitrosococcus,* and Nitrosospira bacteria, and then to nitrate-nitrogen ($NO_3$-N) by facultative chemolithotrophic bacteria *Nitrospira*, and *Nitrobacter* [23]. The results showed that in summer the nitrite and nitrate concentrations in the BAF effluent were higher than other seasons (Fig. 4). The residual values reached some times to 13.5 mg/l for $NO_3$ and 1.8 mg/l for $NO_2$, while in winter and fall seasons, where the temperature decreased, the concentrations of $NO_3$ and $NO_2$ were ranged between 0.002 and 1.0 mg/l.

### 3.2.3. Pathogenic removal

Removal of pathogenic organisms is one of the main objectives of municipal wastewater treatment for developing countries as it signifies the risk factor for public health. Many countries, like Egypt, have stringent standards regarding the presence of pathogens in treated wastewater as they directly affect the health and sanitation conditions of the population [24]. It is well understood that anaerobic reactors does not significantly contribute to the removal of Coliforms [25]. Slight removal of Coliforms was achieved using the P-UASB. The geometric mean of total coliform and fecal coliform counts in the P-UASB effluent in summer was reduced by only 1.3 and 1.2 logs. However, only 0.17 logs of Coliforms were removed in winter with a residual value of $2.1 \times 10^6$ MPN/100 ml. Feng et al. [26] reported that the anaerobic process had a certain effect on the removal of pathogenic species such as total coliform and fecal coliform, but it is necessary to take further appropriate post-treatment process to guarantee the effluent safety. The results depicted in Table 2 shows the average bacterial indicators counts from the different treatment steps during different seasons.

The results indicated that the efficiency of the BAF unit in summer was higher than in winter. BAF removed nearly 3 logs in the summer, while only 1.4 logs were removed in winter. Furthermore, a substantial drop of 4 logs in total and fecal coliform counts

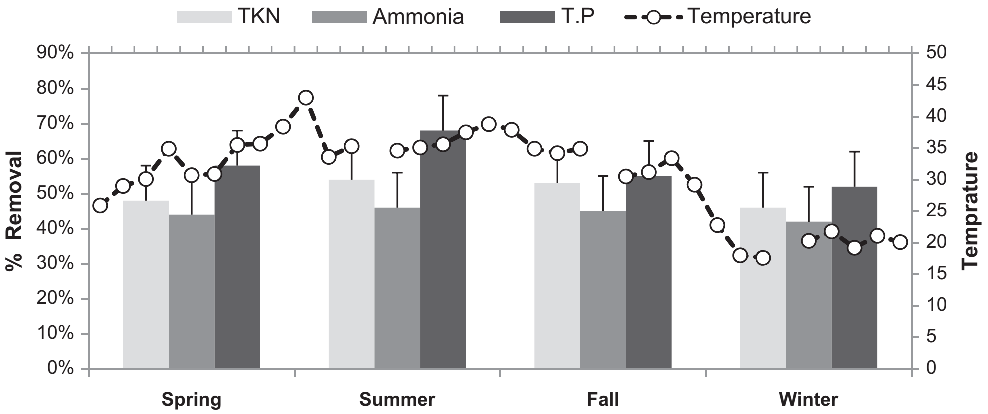

Fig. 3. Overall average removal efficiencies of TKN, ammonia, and T.P during different seasons.

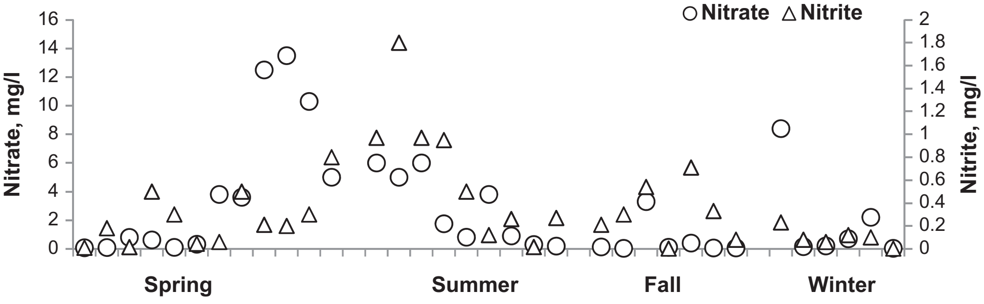

Fig. 4. Variations of $NO_2$ and $NO_3$ concentrations during different seasons.

Table 2
Average total and fecal coliform counts and their removal during different seasons in the effluent from P-UASB, BAF, and IPS

| Parameters | Unit | Spring | | Summer | | Fall | | Winter | |
|---|---|---|---|---|---|---|---|---|---|
| | | Effluent | Logs removal | Effluent | Logs removal | Effluent | Logs removal | Effluent | Logs removal |
| | | *P-UASB* | | | | | | | |
| Total coliforms | MPN-Index/100 ml | 7.6 × $10^5$ | 0.6 | 1.8 × $10^5$ | 1.32 | 2.1 × $10^5$ | 1.3 | 2.1 × $10^6$ | 0.17 |
| Fecal coliforms | MPN-Index/100 ml | 2.8 × $10^5$ | 0.8 | 1. 3 × $10^5$ | 1.2 | 1.9 × $10^5$ | 1.14 | 2.4 × $10^5$ | 0.22 |
| | | *BAF* | | | | | | | |
| Total coliforms | MPN-Index/100 ml | 2.11 × $10^4$ | 2.08 | 3.3 × $10^3$ | 3.06 | 1.4 × $10^4$ | 2.5 | 1.1 × $10^5$ | 1.44 |
| Fecal coliforms | MPN-Index/100 ml | 1.2 × $10^4$ | 2.17 | 2.5 × $10^3$ | 3.08 | 9.9 × $10^3$ | 3 | 3.8 × $10^4$ | 1.48 |
| | | *IPS* | | | | | | | |
| Total coliforms | MPN-Index/100 ml | 8.1 × $10^2$ | 3.5 | 8.1 × $10^2$ | 3.67 | 1.8 × $10^3$ | 3.39 | 4.2 × $10^4$ | 1.87 |
| Fecal coliforms | MPN-Index/100 ml | 5.6 × $10^2$ | 3.51 | 2.5 × $10^2$ | 4.08 | 1.2 × $10^3$ | 3.2 | 1.8 × $10^4$ | 1.8 |

has been achieved in the final effluent after the IPS unit during summer with a residual count of 2.5×$10^2$ MPN/100 ml. However, the removal efficiency decreased in winter and only 1.8 logs was removed in the final effluent. To assure safe reuse, disinfection is required to comply with permits stated in the National Standards for the reuse of treated wastewater in irrigation (fecal coliform < 1 × $10^3$ MPN/100 ml).

## 4. Biogas and biomass production in the treatment system

The biogas produced from the same P-UASB was reported by Abou-Elela et al. [1] The methane content was ranged between 72 and 77% of the total biogas. Also, the biogas included some other gases such as nitrogen, $NH_3$, $CO_2$, CO, and $N_2O$. Also, the results of sludge analysis in P-UASB showed that the total weight of the sludge was 67.35 g/l, with an organic content of 39.15 g/l. Moreover, the analysis of sludge in BAF reactor indicated that the total weight of the sludge was 16.37 g/l, with an organic content of 13.5 g/l.

## 5. Conclusion

The use of a pilot scale P-UASB followed by BAF reactors proved to be a very sustainable and promising approach for the treatment of municipal wastewater. The NWPF was used, for the first time, as a bio-film holder in both UASB and BAF. It enhanced the performance of the integrated treatment system. Regardless of the variations in the ambient temperature from 10–40˚C, the performance of the treatment system was very satisfactory. The overall removal rates of COD, BOD, and TSS were 88.9, 90.6, and 92.4%, respectively. Moreover, the system was capable to remove 4 logs of total coliform and fecal coliform.

However, slight improvement in the above-mentioned parameters was observed in summer. As a conclusion, the integrated treatment system produced a quality of effluent amenable for reuse according to the National Regulatory Standard for wastewater reuse. The treatment system is cost effective, has a small footprint, modular and can be applied for wastewater treatment in rural areas and small communities.

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