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Seasonal variation pattern of physicochemical and microbial parameters in a wastewater treatment plant

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ABSTRACT

Wastewater discharge contains a high level of contaminants that require sufficient treatment for further reuse and legitimate applications. This study examined the effect of seasonal variations on treatment performance. Data was generated daily from January 2013 to December 2016, analyzing the samples from different stages that is, influent, secondary and tertiary effluents. The results for microbial parameters showed that in the influent, fecal coliforms had the highest levels in fall, while the coliform count had the highest levels in winter, with *Salmonella*, fecal streptococci and fungi presenting better resistance and survival in spring. However, the physicochemical parameters, for example, pH and conductivity, of the influent and treated effluents did not vary with season, but slight variations occurred in all other parameters. In fall, chemical oxygen demand, volatile suspended solids and total suspended solids showed minimal changes in the tertiary-treated effluent, while biochemical oxygen demand$_5$ showed no significant changes in all seasons. The coefficient of variation and coefficient of reliability showed minimal variability in plant performance and highly reliable conditions for water reuse in irrigation, indicating compliance with effluent discharge standards and stable operating conditions. Identifying seasonal variations in parameters promote the optimization of the operational conditions and performance of wastewater treatment plants.

Keywords: Plant performance; Physicochemical parameters; Microbial parameters; Wastewater treatment; Reliability analysis

1. Introduction

Wastewater treatment has been increasingly utilized due to the wide range of pollutants produced from industries such as the pharmaceutical industry and chemical and biomedical manufacturing plants, causing complex and harmful effects to water [1]. Therefore, environmental authorities worldwide require the implementation of a treatment process before discharging wastewater into water-courses or reusing it for agriculture or other applications to minimize hazards to the environment and to protect public health [2,3]. The practice of wastewater treatment has been recognized and carried out since approximately the sixteenth century, with gradual improvements in chemical, physical and biological treatments and major developments throughout the 1900s until the current date [4]. Thus, with the advanced technologies and better understanding of the treatment processes available today, treatment can be conducted to several purity levels to meet water quality standards based on the application purpose, for example, irrigation, support for aquatic life or use as drinking water [5–8]. Such treatments are necessary because of the deterioration of the quality and quantity of freshwater is becoming a major and growing issue, as are problems that occur in ecosystems [9,10]. Moreover, treatment processes may involve physical, chemical or biological technologies or be comprised of a combination thereof. To this end, in a typical wastewater treatment plant (WWTP), several stages are involved to achieve the removal of contaminants to

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the required specifications. The process includes the first stage of pretreatment and primary treatment, for example, sedimentation and oil & grease (O&G) removal, to provide suitable raw wastewater for the following stages. The second stage is more important than the previous stage and aims to degrade the biological content, such as by utilizing trickling filtration or activated sludge. The final stage, known as tertiary treatment, increases the water quality to meet the desired requirements for different application purposes and includes steps such as flocculation, ion exchange and coagulation [5]. Furthermore, the physical quality of wastewater is determined by its physical parameters, such as temperature, density, turbidity, solids content, color and odor. The chemical quality of wastewater is determined by the chemical parameters of organic and inorganic components, while the microbiological quality parameters include microorganisms such as bacteria, fungi, algae, coliform bacteria, *Escherichia coli* (*E. coli*) and fecal streptococci [11]. The influent wastewater load is uncontrolled and constantly varies in flow and concentration. Previous attempts to model plant performance include mathematical modeling [12], statistical analyses [13] and artificial neural networks [14]. Although many studies have assessed the performance of WWTPs, only a few have focused on the effects of seasonal variations on plant performance [15]. Therefore, this study was conducted to determine the effect of seasonal variations on both physicochemical parameters, such as temperature, pH, conductivity, total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), O&G, and dissolved oxygen (DO), and microbiological parameters, such as total coliforms, fecal coliforms, fecal streptococci, fungi and *Salmonella*. A municipal WWTP in Kuwait, namely, the Kabd WWTP, was considered in this study as a model of a municipal WWTP operating in a hot and dry climate region to perform an analysis of plant performance data.

2. Materials and methods

2.1. Study area and sample collection

The Kabd WWTP is located south of Kuwait City and west of residential areas and is considered to be the most recent plant in Kuwait. The plant was constructed in 2010 and was initiated in 2012 to serve a total population of approximately 600,000. The design capacity of the plant is 180,000 m^3/d, with peaks of up to 270,000 m^3/d. Currently, the average daily inflow is 150,000 m^3/d [16]. The study was conducted over a 4 y period from January 2013 to December 2016 by collecting samples from three stages: influent, secondary effluent (activated sludge) and tertiary effluent (filtration and chlorination). Automatic supervisory control and data acquisition system is used in the Kabd WWTP to instantaneously measure flow parameters. All tests and parameter measurements were performed in the plant laboratory.

2.2. Data measurement and analysis

The study included 15 parameters obtained from the Kabd WWTP. Their daily performance was statistically analyzed to examine variations in the water quality parameters, identify the interrelationships between parameters, for example, BOD, COD and TSS, and determine the efficiency of the plant. The data analysis period was divided into four seasons for each year: winter (December, January, and February), spring (March, April, and May), summer (June, July, and August) and fall (September, October, and November) based on climatic conditions. The data were analyzed and interpreted using IBM SPSS Statistics 23.0 software using several tools, such as descriptive analysis. Table 1 demonstrates the standard method used for each parameter along with the technique applied for the measurement.

Table 1
Standard testing methods and equipment used in the Kabd WWTP laboratory

Parameter		Standard method	Technique used
Physicochemical parameters			
Temperature, (°C)		–	Thermometer
pH, (–)		APHA 4500 HB	pH meter
Conductivity, (μS/cm)		APHA 2510B	Conductivity meter
TSS, (mg/L)		APHA 2540D	Gravimetry
VSS, (mg/L)		APHA 2540E	Gravimetry
SVI, (cm^3/dm^3)		APHA 2710D	Calculation
DO, (mg/L)		APHA 4500 0G	DO meter
BOD_5, (mg/L)		APHA 5210B	5-day BOD test (manual)
COD, (mg/L)		APHA 5220D	Colorimetric method
O&G, (mg/L)		APHA 5520B	Liquid–liquid partition-gravimetric method using *n*-hexane
Microbial parameters			
Total coliforms	CFU/mL	APHA 9222B	Membrane filtration method
Fecal coliforms	CFU/mL	APHA 9222D	Membrane filtration method
Salmonella	APHA 9260B	APHA 9260B	Membrane filtration method

3. Results and discussion

3.1. Daily wastewater flow rate

Measuring the wastewater influent flow rate is important for determining a plant's efficiency. The concentration of microorganisms decreases as the flow rate increases; this decrease primarily depends on the degree of dilution. Fig. 1 shows that the average daily flow from January 2013 to February 2014 was 81,607 m^3/d. In this period, the wastewater flow was divided between the Kabd WWTP and Al-Jahra WWTP. In March 2014, the Al-Jahra WWTP was closed, and the total wastewater flow was redirected to the Kabd WWTP, where the average daily wastewater inflow rate from March 2014 to December 2016 reached 150,346 m^3/d and the maximum daily flow rate in this period was 187,193 m^3/d, which represents an increase of 24.5% in flow rate [16]. Clear variations in the wastewater flow rate are observed between months, and in January, February and August, the daily flow rate decreased because most people spend their vacations outside Kuwait in this period. The average daily tertiary effluent flow rate from January 2013 to February 2014 was 80,222 m^3/d, and from March 2014 to December 2016, it was 148,292 m^3/d, as shown in Fig. 1. The tertiary effluent overflow is pumped for site irrigation through the data monitoring center (DMC); the center, which is operated by the Ministry of Public Works to collect tertiary-treated effluent, includes storage tanks that hold water for irrigation use and receives wastewater effluents from all the WWTPs in Kuwait through pressure lines with a capacity of 340,000 m^3/d.

3.2. Seasonal variations

3.2.1. Physicochemical parameters

3.2.1.1. Temperature

Variations in the water temperature in the plant were due to seasonal climatic variations. The average daily temperatures of the raw wastewater influent, the secondary and tertiary treated wastewater and the aeration (Aer) tank were very close, and the reported average values were 23.4°C in winter, 28.2°C in spring, 30.53°C in fall and 32.4°C in summer (Fig. 2). The seasonal variations in temperature showed a cyclic pattern, with the lowest values reported in winter and the highest values occurring in summer. The cyclic pattern is in alignment with a previous study conducted in Japan, which reported a similar cyclic pattern, as it recorded the highest values in summer, reaching 30.1°C, and the lowest in winter, with a value of 6.2°C [17]. Moreover, the maximum daily water temperatures were 28.6°C in winter, 34.4°C in spring, 35.4°C in fall and 36.7°C in summer, while the minimum daily water temperatures were 15.6°C in winter, 17.6°C in spring, 18.2°C in fall and 20.55°C in summer, as shown in Fig. 2. Variations in water temperature affect the treatment system, especially the biological treatment system and microbial population. The ambient temperature in Kuwait occasionally rises to 50°C during summer, which causes nitrification problems in the WWTP. The temperature values obtained in this study are in agreement with those observed by [18] for another WWTP in Kuwait (the Riqqa plant), which reported an average water temperature in the plant of 20°C during winter.

3.2.1.2. pH

The average daily pH of the influent wastewater was 7 in spring and 7.2 in winter, summer and fall, while the average pH value in the final effluent was slightly lower, averaging 6.9 in spring and 7.1 in winter, summer and fall. All values recorded were within the acceptable limits established by the Kuwait Environment Public Authority (KEPA) (6.5–8.5). The observed values are an indication of the absence of industrial wastes in the plant influent. However, a similar statistical analysis of wastewater composition in Turkey was performed, in which an insignificant

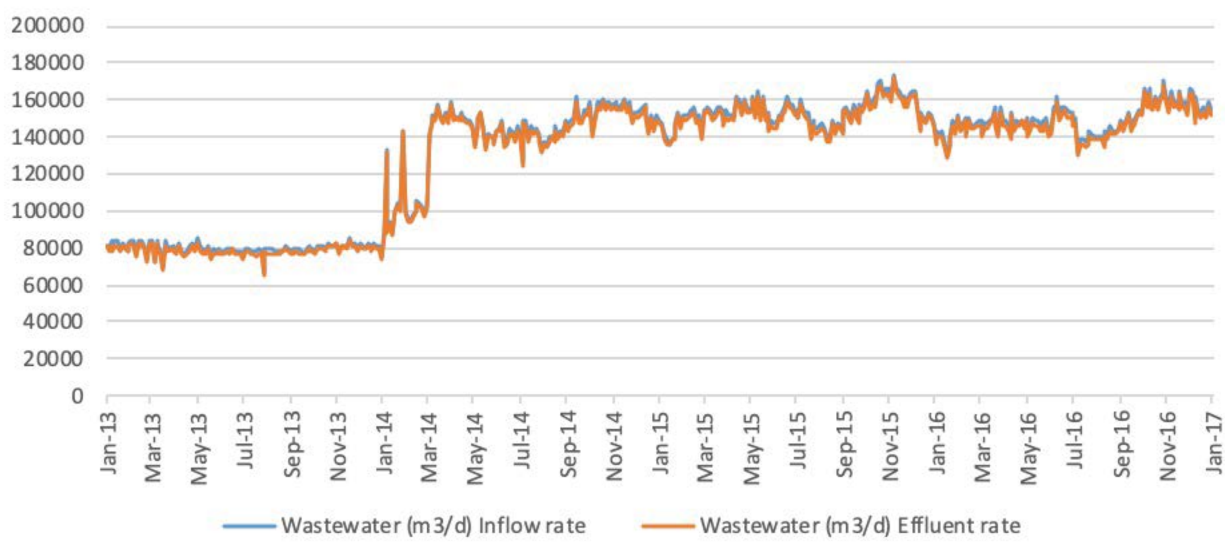

Fig. 1. Variations in the influent and effluent flow rates.

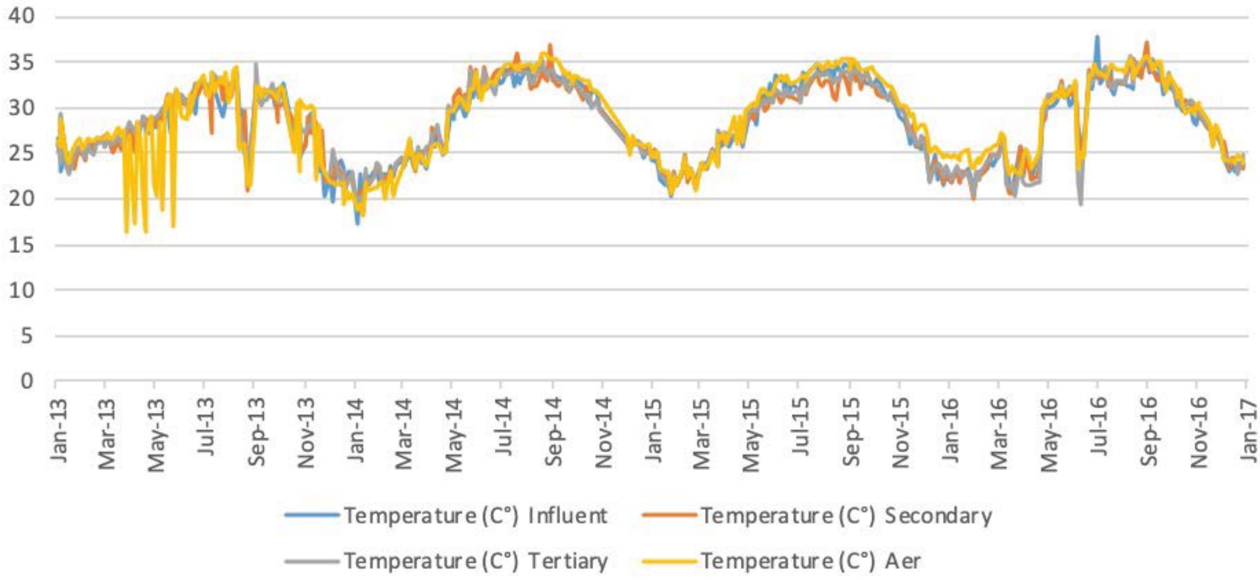

Fig. 2. Variations in the temperature of the raw wastewater influent, secondary effluent, tertiary effluent and aeration tank.

and negligible difference between the pH values in summer and winter was observed, with values of 7.5 and 7.8, respectively [19]. In comparison, the average pH in the Riqqa WWTP in Kuwait were 6.5 for the influent and 8.5 for the final effluent wastewater [18]. The typical pH values of domestic wastewaters range from 6.9 to 7.2 [11,20]. Furthermore, the pH value affects the microbial activity in the biological treatment stage, and extreme values indicate the presence of industrial effluents in the wastewater.

3.2.1.3. Conductivity

The average daily conductivities of the influent wastewater and final effluent were 1,362; 1,463; 1,493; 1,598 µs/cm for the influent and 1,266; 1,344; 1,357; 1,486 µs/cm for the effluent in the winter, spring, fall and summer seasons, respectively. Higher values occurred in summer. All values reported were below the standard limit regulated by the Kabd contract (2,000 µs/cm). Electrical conductivity represents the ability to conduct electrical current, and it is related to the ion concentration and total dissolved solids (TDS) of the wastewater, which is approximately 1,200 mg/L. In the Riqqa WWTP, the conductivity ranged between 1,300 and 2,400 µs/cm in the influent and between 970 and 1,100 µs/cm in the secondary-treated effluent [18]. The electrical conductivity values were higher than those in previous studies; for example, Olabode et al. [10] analyzed the properties of two WWTPs during four different seasons and reported an electrical conductivity range of 923.00 to 1,294.17 µS/cm, with the lowest value being recorded in fall and the highest in summer. Perhaps the conductivity and TDS of municipal wastewater in Kuwait are higher than typical values reported in the literature [11,20], which would presumably be due to the infiltration of brackish subsurface waters into the wastewater collection system. The toxic concentration of a specific ion is associated with the presence of salts, which will affect plant growth if wastewater effluent is used for irrigation. Moreover, high conductivity affects microbial activity in the biological treatment stage.

3.2.1.4. Total suspended solids and volatile suspended solids

In the raw wastewater inflow, the average daily TSS values were 181.22, 173.46, 170.5 and 159.21 mg/L in summer, spring, winter and fall, respectively. The maximum average concentration of TSS in the final effluent after tertiary treatment, which depends on the process removal efficiency, occurred in the fall and winter seasons (4.75 and 5.8 mg/L, respectively), as shown in Fig. 3. The effluent values were below the standard limits regulated by KEPA (15 mg/L). TSS is used to evaluate the performance of a WWTP, and high values of suspended solids in the sludge are associated with a high sludge age and indicate an increase in the wastage rate. In comparison, in the Riqqa WWTP, the TSS in the influent and effluent ranged between 100 and 300 mg/L and between 1 and 10 mg/L, respectively [18]. In addition, a study in Kenya was performed to evaluate the impact of seasonal variations between wet and dry seasons on wastewater treatment performance.The TSS in the influent ranged between 60 to 240 mg/L during the wet season varying more than the dry season which ranged between 90–200 mg/L [21]. In contrast, the average daily VSS in the raw wastewater in Kabd plant inflow was 46.96 mg/L, while the average concentration of VSS in the final effluent was 0.9 mg/L in fall, 1.3 mg/L in winter and spring, and 1.6 mg/L in summer (Fig. 4). However, the average value in summer reached 128 mg/L, while in winter, a lower average value of 18 mg/L was obtained. In comparison, a similar study was conducted in Spain, reporting an average influent TSS in winter of 252.6 mg/L; in summer, the average value observed was lower, reaching 200 mg/L [22]. It can be seen from Figs. 3 and 4 that although the TSS and VSS concentrations of the raw wastewater oscillate and reflect seasonal variations, their concentrations in the tertiary effluent remain

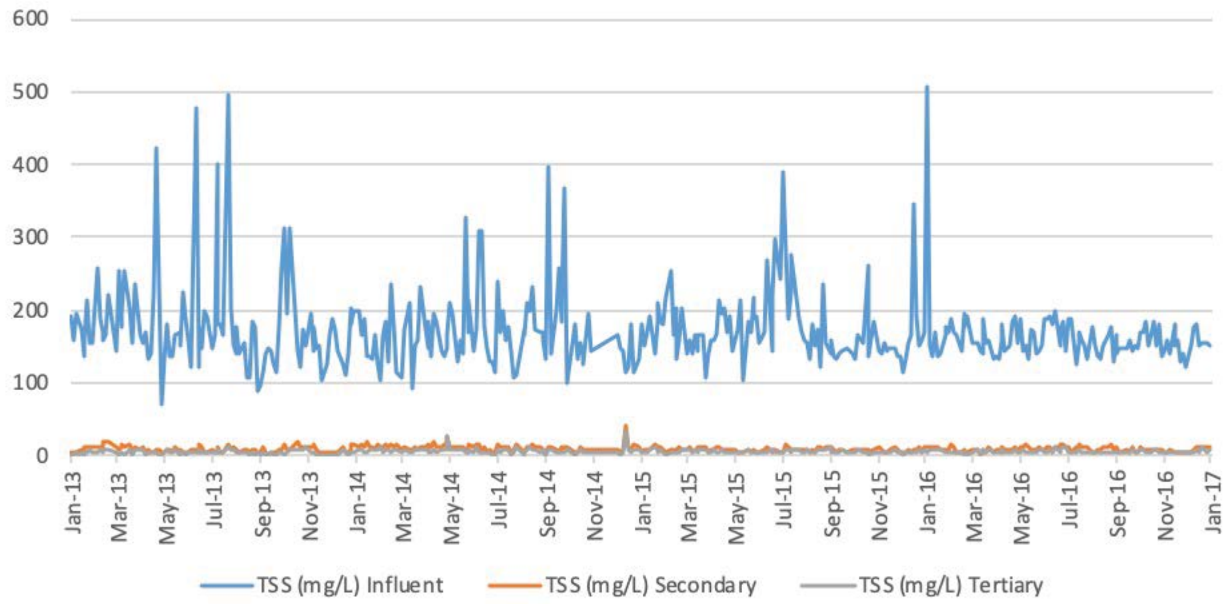

Fig. 3. Variations in TSS in the raw wastewater inflow, secondary effluent and tertiary effluent.

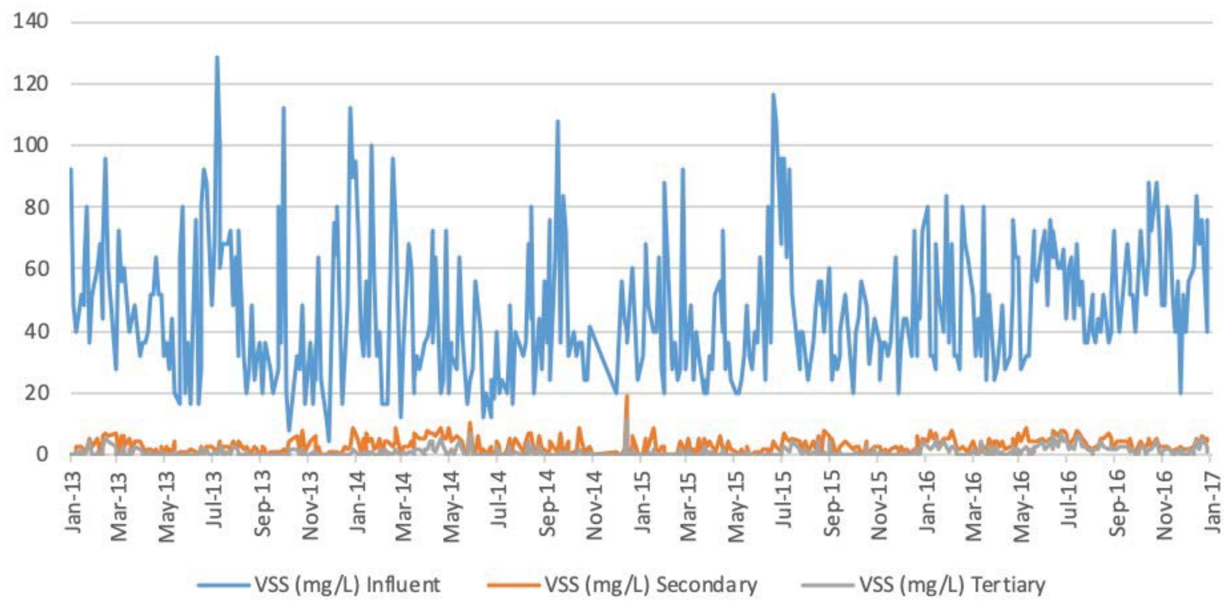

Fig. 4. Variations in VSS in the raw wastewater inflow, secondary effluent and tertiary effluent.

almost constant at very low levels. This consistency reflects the high efficiency of the secondary clarifiers and tertiary filters in removing such solids and in improving the effluent water quality.

3.2.1.5. Sludge volume index

The sludge volume index (SVI) is the volume occupied by 1 g of sludge after settling (30 min). It describes how well the sludge from the aeration tank settles and compacts. The SVI in the aeration tanks increased as the temperature increased, and the highest average daily value was 122 mL/g in summer, which still indicates very good settling characteristics. As shown in Fig. 5, the SVI values in 2014 suddenly increased, reaching 333 mL/g, which indicates that the bulking sludge had poor settling properties. An SVI value >150 mL/g indicates a high population of filamentous bacteria, and such conditions were observed in the Kabd WWTP in the summer of 2014. After contacting the facility manager of the Kabd WWTP, it was determined that filamentous bacteria started growing and suddenly reproduced in 2014, which affected the treatment process in the plant. An SVI value ≤ 70 mL/g indicates the poor settling of small aggregates, while a value of 150 mL/g indicates the rapid settling and compaction of large flocs. Fig. 5 presents the seasonal variations in SVI in the activated sludge aeration tanks.

3.2.1.6. Dissolved oxygen

The average daily DO value was 2.5 mg/L, and the highest daily DO values in the aeration tanks were 4.76, 5.04, 8.43 and 9.07 mg/L in summer, fall, spring and winter, respectively. These findings indicate a decreasing DO level with increasing temperature. In comparison [10], reported an average DO of 1.3 to 5.5 mg/L in two investigated WWTPs, explaining the relatively high values that were recorded in fall, summer and spring by the long daylight hours and bright sunlight. If the DO concentration is low in the aeration tank, then the activity of aerobic microorganisms will be inhibited, which will adversely affect BOD removal. The DO concentration in the aeration tank should not be lower than 2 mg/L. At a DO value <2 mg/L, the nitrification rate will be improved in a reactor with high BOD loads; however, at a DO value <4 mg/L, the operation will not be improved significantly.

3.2.1.7. Biochemical oxygen demand

The average daily BOD_5 of the influent wastewater was 244, 250, 251, and 272 mg/L in fall, spring, summer and winter, respectively, while the average BOD_5 of the tertiary-treated effluent was similar in all seasons and ranged from 4 to 5 mg/L despite seasonal variations in the influent BOD_5 (Fig. 6). The recorded values of the effluent were within the acceptable limit established by KEPA (20 mg/L). BOD_5 was high in comparison with values reported a study conducted in the Izmir WWTP, Turkey, where the average BOD_5 was 194.241 mg/L in winter and 106.108 mg/L in summer [19]. Furthermore, the average overall BOD_5 removal efficiency in the Kabd WWTP was 98.05%. However, similarly, a study conducted in Poland showed a better overall removal efficiency of 99.25%, with values ranging from 99% to 99.38%, reaching the highest value in summer and lowest in winter [23].

3.2.1.8. Chemical oxygen demand

The average daily COD for the influent wastewater was 598, 631, 643, and 873 mg/L in fall, winter, summer and spring, respectively, while the average COD in the tertiary-treated effluent was 19.9 mg/L in fall, 24.1 mg/L in summer, 24.9 mg/L in spring, and 25.5 mg/L in winter (Fig. 7), despite seasonal variations in the influent COD. The effluent values reported for COD were below the standard limit set by KEPA (100 mg/L). In comparison, a study conducted in Izmir, Turkey, found a higher average influent COD in winter than in summer, with values of 529.106 and 342.206 mg/L, respectively [19]. The COD concentrations in the Kabd WWTP showed similar values in winter but higher values in summer. The BOD_5/COD ratio ranged between 0.3 and 0.8 in the influent wastewater and between 0.1 and 0.3 in the final effluent, which may indicate that the wastewater organics in this plant are moderately biodegradable. The average COD removal efficiency in this plant was 96.07%. In comparison, [23] reported a lower overall removal efficiency of 94.73%, with values in the four seasons ranging from 93.44% to 95.35%; the highest value was recorded in summer, while the lowest was recorded in winter, which indicates high COD removal performance despite the presence of a high COD concentration in the influent.

3.2.1.9. Correlation between BOD_5 and COD

There was a distinct linear correlation between the BOD_5 and COD values reported in this study. The average BOD_5/COD ratio was found to be 0.44, which indicates

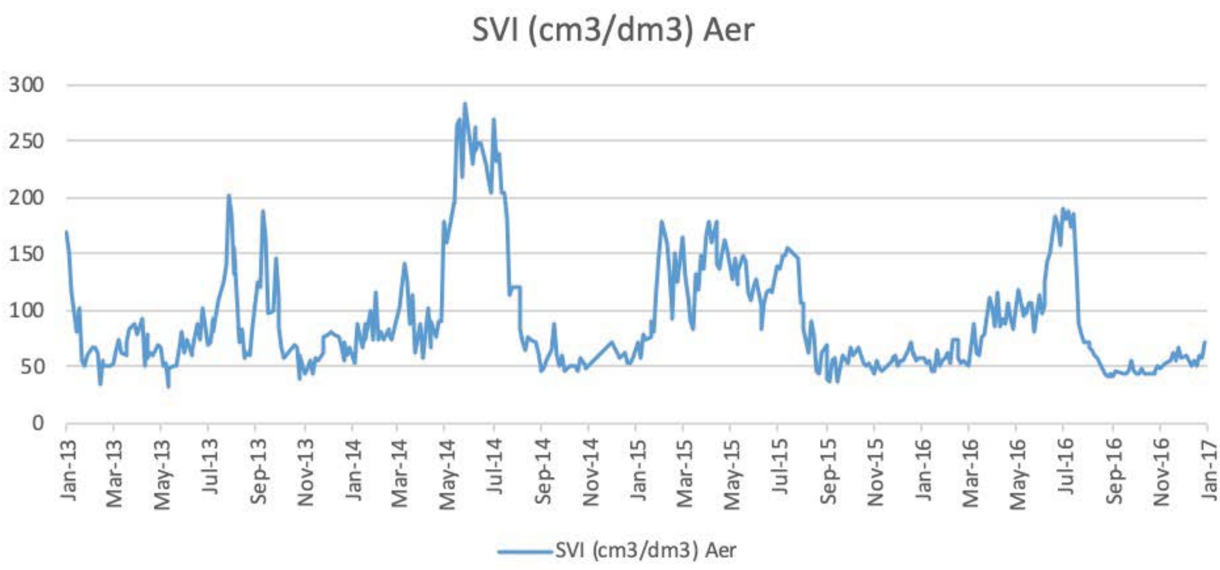

Fig. 5. Variations in SVI in the aeration tanks.

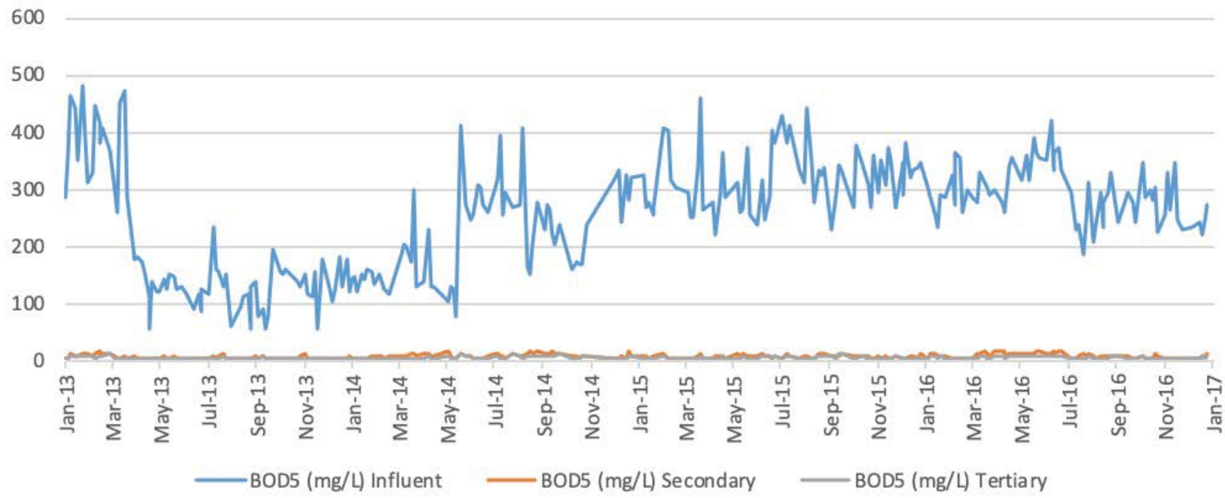

Fig. 6. Variations in BOD_5 in the raw wastewater inflow, secondary effluent and tertiary effluent.

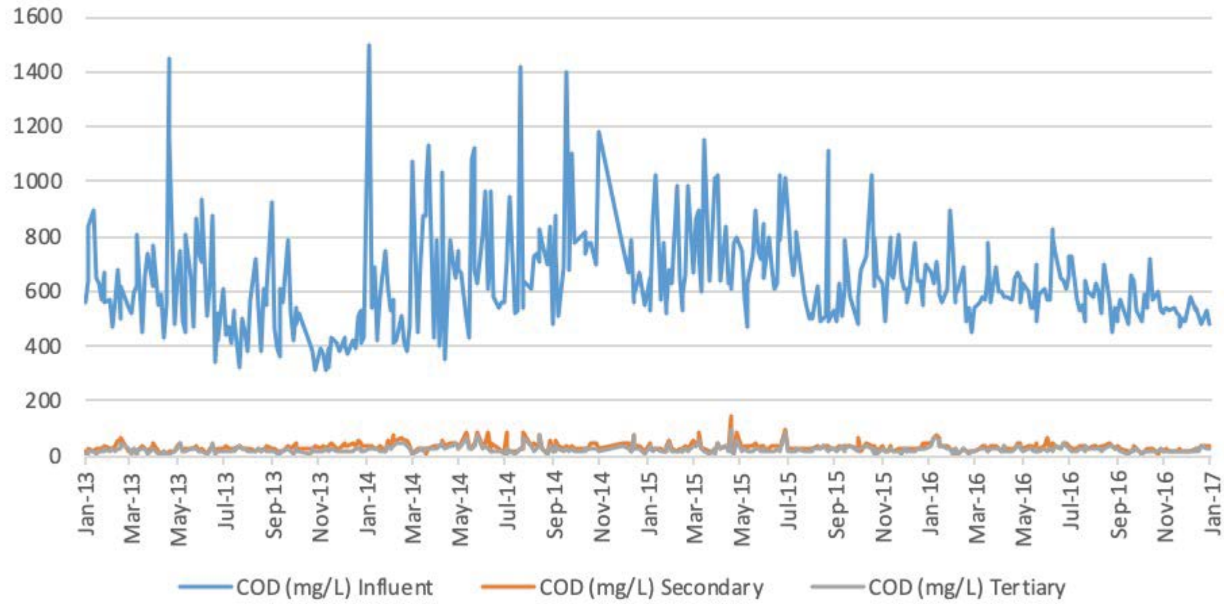

Fig. 7. Variations in COD in the raw wastewater inflow, secondary effluent and tertiary effluent.

that the organic compounds of the wastewater are moderately biodegradable. This assessment is accurate since the wastewater received at this plant is primarily domestic and no dumping of industrial wastewater is legally permitted in this plant.

3.2.1.10. Oil and grease

Fig. 8 illustrates that the mean O&G content in the influent wastewater was 42.6 mg/L and that it occasionally reached a maximum value of 191 mg/L. A problem associated with O&G removal was observed in the secondary treatment stage during the years 2015 and 2016. As stated previously, before 2014, filamentous bacteria started growing, and their sudden reproduction affected the treatment processes in the plant. The average concentration of O&G in the secondary treatment effluent was 0.99 mg/L in summer. The values in the effluent were below the limit regulated by KEPA (5 mg/L). Similarly, in the Riqqa WWTP in Kuwait, the O&G content ranged between 10 and 40 mg/L for the influent and 1 and 10 mg/L for the secondary effluent [18]. It can be seen from Fig. 8 that unlike other parameters studied in this plant, the O&G concentration in the secondary-treated effluent oscillated with seasonal variations in the influent since O&G can escape from the preliminary treatment stage (which does not include primary clarifiers), pass directly to the aeration tanks and float to the surface with rising diffused aeration bubbles.

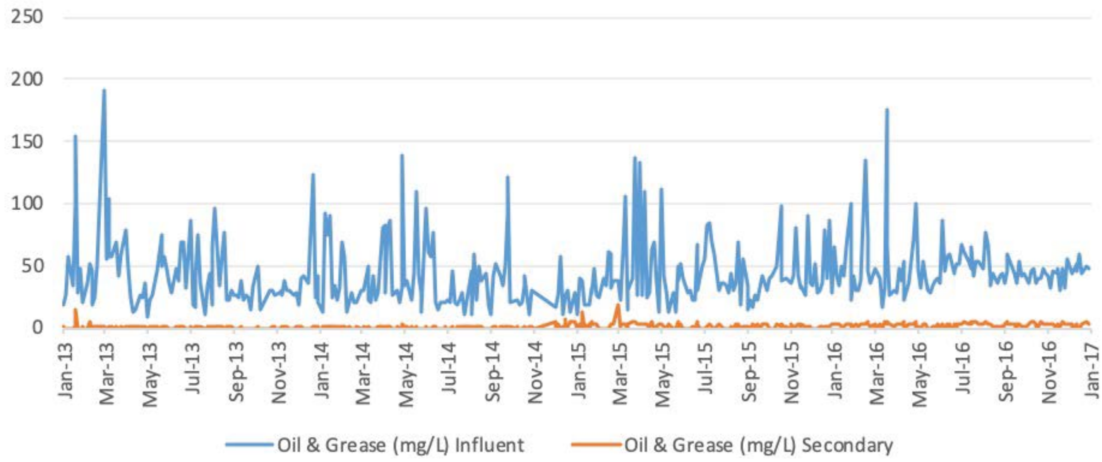

Fig. 8. Variations in O&G in the raw wastewater influent and secondary effluent.

3.2.2. Microbial parameters

3.2.2.1. Total coliforms

The highest average total coliform content in the raw wastewater ranged from 2.9E+9 MPN/100 mL in spring to 3.2E+9 MPN/100 mL in winter, while in the tertiary treatment effluent, the values observed were low and were very close in winter (5.9 MPN/100 mL) and spring (6.0 MPN/100 mL). The reported effluent values were below the KEPA standard limit (400 MPN/100 mL). However, a study conducted in India showed the opposite behavior: the highest total coliform content in the influent reached 7.9E+8 MPN/100 mL in spring, and the lowest value was recorded in winter, with a value of 4.2E+8 MPN/100 mL [24]. The effluents in spring and winter contained 4.6E+7 MPN/100 mL and 5.4E+7 MPN/100 mL, respectively. Coliform bacteria are an indicator of the microbial pollution level of wastewater.

3.2.2.2. Fecal coliforms

Fecal coliforms survived better in the influent in spring (1.52E+8 MPN/100 mL) and winter (2.09E+8 MPN/100 mL), and in the tertiary treatment stage, the average values were 0.81, 1, 1.1 and 1.3 MPN/100 mL in winter, summer, fall and spring, respectively. The effluent values were within the accepted limit set by KEPA (20 MPN/100 mL). The study performed by [24] reported the highest value of 8.5E+7 MPN/100 mL in spring and the lowest value in winter, reaching 5.5E+7 MPN/100 mL. However, the effluent values were 6.3E+6, 5.5E+6, 5.2E+6 and 7.2E+6 MPN/100 mL in spring, fall, summer and winter, respectively. Fecal coliforms survive in wastewater at temperatures between 20°C and 90°C over a maximum time period of 60 d [18].

3.2.2.3. Salmonella

Salmonella survived better in spring and was present at an average concentration of 1.52E+8 MPN/100 mL in the influent and 1.3 MPN/100 mL in the tertiary treatment effluent. *Salmonella* survives in wastewater over a maximum period of 60 d; the *Salmonella* content usually ranges between 10^4 and 10^5 MPN/100 mL in the influent, although it is reduced to 0 in the final effluent [18].

3.2.2.4. Fungi

Fungi resist and survive better in spring and were present at an average concentration of 1.00E+06 MPN/100 mL in the influent wastewater and 11.8 MPN/100 mL in the tertiary-treated effluent. In a study conducted in India, the average fungi concentrations present in the influent during summer and winter were reported to be 7×10^6 CFU/mL and 45×10^6 CFU/mL, respectively [15]. Fungi can survive better under low pH, moisture and nitrogen conditions, and their values usually range between 10^4 and 10^6 in the influent and are reduced to 0 in the final effluent [18].

3.2.2.5. Fecal streptococci

Fecal streptococci survive better in spring and were present at an average concentration of 1.39E+07 MPN/100 mL in the influent wastewater and 13.31 MPN/100 mL in the tertiary-treated effluent. The results showed lower fecal streptococci concentrations than normal; for example, a study performed in India reported that the average influent value in spring reached 8.5E+6 MPN/100 mL, while the effluent value was 1.4E+6 MPN/100 mL [24]. Fecal streptococci are an indicator of a fecal contamination source when combined with fecal coliforms, and the values usually range between 10^3 and 10^4 in the influent, whereas they are reduced to 0 in the final effluent [18].

The influent and effluent average values of the physicochemical and microbial parameters reported for the entire study period covering the four seasons are summarized in Tables 2–5.

3.3. Plant efficiency

3.3.1. Removal efficiency

Plant efficiency depends on the removal of different parameters; in this study, the plant efficiency is determined in terms of the removal of BOD_5, COD, TSS, O&G, ammonia-nitrogen (NH_3–N) and PO_4^{3-}.

As shown in Table 6, the overall efficiency of the Kabd WWTP is better than those of other plants in Kuwait (Ardiya and Riqqa) and in Dubai (Al-Awir) since the Kabd WWTP is the newest plant in Kuwait and the plant is not overloaded. Additionally, the suspended solids removal efficiency is better during winter than during summer

Table 2
Average values of physicochemical parameters in the influent

Parameter	Summer	Winter	Spring	Fall
Temperature, (°C)	32.4	23.4	28.2	30.53
pH	7.2	7.2	7	7.2
Conductivity, (µs/cm)	1,598	1,362	1,463	1,493
TSS, (mg/L)	181.22	170.5	173.46	159.21
VSS, (mg/L)	50.2	52	42.8	42.6
DO, (mg/L)	–	–	–	–
BOD_5, (mg/L)	251	272	250	244
COD, (mg/L)	643	631	873	598
O&G, (mg/L)	44.5	43	44.5	37.9

Table 3
Average concentrations of microbial parameters in the influent

Parameter	Summer	Winter	Spring	Fall
Total coliforms, (MPN/100 mL)	2.4E+9	3.28E+9	2.9E+9	2.66E+9
Fecal coliforms, (MPN/100 mL)	1.2E+8	2.09E+8	1.52E+8	1.16E+8
Salmonella, (MPN/100 mL)	2.27E+7	4.938E+7	5.15E+7	2.46E+7
Fungi, (MPN/100 mL)	7.54E+5	9.2E+5	1.0E+6	7.56E+5
Fecal streptococci, (MPN/100 mL)	1.17E+7	1.205E+7	1.39E+7	1.39E+7

Table 4
Average values of physicochemical parameters in the effluent

Parameter	Summer	Winter	Spring	Fall
Temperature, (°C)	32.4	23.4	28.2	30.53
pH	7.1	7.1	6.9	7.1
Conductivity, (µs/cm)	1,486	1,266	1,344	1,357
TSS, (mg/L)	5.95	5.8	5.9	4.75
VSS, (mg/L)	1.6	1.3	1.3	0.9
DO, (mg/L)	3.84	3.5	3.7	3.74
BOD_5, (mg/L)	5.2	4.35	4.9	4.05
COD, (mg/L)	24.1	25.5	24.9	19.9
O&G, (mg/L)	0.99	1.56	1.18	1.03

Table 5
Average concentrations of microbial parameters in the effluent

Parameter	Summer	Winter	Spring	Fall
Total coliforms, (MPN/100 mL)	1.89	5.9	6	1.98
Fecal coliforms, (MPN/100 mL)	1	0.81	1.3	1.1
Salmonella, (MPN/100 mL)	0.89	0.24	1.3	0.3
Fungi, (MPN/100 mL)	3.41	10.19	11.8	3.33
Fecal streptococci, (MPN/100 mL)	3.65	6.63	13.31	3.22

Table 6
The efficiency of the plant

Parameter	Abbreviation	Unit	Efficiency of secondary effluent (Kabd WWTP)	Overall efficiency (Kabd WWTP)	Overall efficiency of plants with similar conditions
Biochemical oxygen demand	BOD_5 (5 d, 20°C)	mg/L	96.98%	98.05%	97.3% Ardiya, Kuwait[a]
Chemical oxygen demand	COD	mg/L	94.66%	96.07%	>90% Riqqa, Kuwait[b]
Total suspended solids	TSS	mg/L	94.52%	96.55%	94.6% Ardiya, Kuwait[a]
Oil & grease		mg/L	96.93%	–	–
Volatile suspended solids	VSS	mg/L	91.78%	97.14%	>90% Riqqa, Kuwait[b]
Ammonia	NH_3–N	mg/L	68.58%	80.2%	75% Al-Awir, Dubai[c]
Phosphate	PO_4^{-3}	mg/L	67.54%	81.62%	–

[a][14]; [b][18]; [c][25].

because high temperatures improve the reproduction of nitrifying bacteria and the production of nitrogen in the final effluent. Moreover, it is evident that the secondary biological treatment stage removes the majority of the organic matter (more than 90%) and, to a lesser extent, ammonia and phosphates (approximately 70%).

3.3.2. Regression analysis

The relationship between the removal performance and related wastewater parameters (physicochemical and microbial) was analyzed by applying linear regression analysis. The results are presented in Tables S1 and S2 in the supplementary file and showed no significant effect of the parameters on the efficiency of the removal process. However, the most significant physicochemical parameters identified in the analysis were TSS and BOD_5.

3.3.3. Standard limits

The Kabd WWTP follows the guidelines of KEPA, and the final effluent satisfies the water quality standards for reuse in irrigation. The results in Table 7 show that the physicochemical parameters in the effluent water at the Kabd WWTP meet the water standard limits for irrigation use for parameters such as temperature, pH, BOD, COD, O&G, conductivity, TSS, TDS, PO_4^{-3}, NH_3–N, turbidity and DO. Additionally, the microbial parameters in the final effluent, such as the coliform count, meet the microbial water standards for reuse in irrigation. The average daily fecal coliform values were 0.25, 0.92, 1.49 and 0.52 MPN/100 mL in 2013, 2014, 2015 and 2016, respectively, and they met the KEPA water standard, which is 20 MPN/100 mL, but slightly exceeded the project contract water standard, which is 0 MPN/100 mL. The average daily *Salmonella* content was 2.25, 0.92, 1.49 and 0.52 in 2013, 2014, 2015 and 2016, respectively, slightly exceeding the water quality standard limit for irrigation use, which is equal to zero.

3.4. Statistical correlations and reliability analysis

Probability plotting of plant performance data provides a pictorial representation of the data, an estimate of the goodness of the fit to the probability model, and estimates of the distribution parameters. Reliability refers to the percentage of time the treated effluent parameters meet the water quality limits [11], which are preset by regulatory authorities such as KEPA in Kuwait.

3.4.1. Probability model

Probability plotting of the performance data was used to determine whether the variations in the performance parameters fit a normal distribution model. Moreover, the coefficient of variation (CV) was calculated as follows:

$$CV = \frac{\text{Standard deviation}}{\text{Mean}} \tag{1}$$

Fig. 9 shows the probability plots of final (tertiary-treated) effluent BOD, COD and TSS in 2013 (number of observations 305) as an example. Similar plots were obtained for other years up to 2018, showing normal distribution of plant performance data with a high coefficient of determination (R^2) values. These probability plots also indicate that based on KEPA water quality standards for effluent reuse in irrigation, there is a zero probability that the plant tertiary-treated effluent concentrations will be exceeded. This conclusion remains true regardless of whether the BOD or COD analysis is based on the "Total" or "Filterable" parameter. In contrast, there is a 0.10 probability that the secondary-treated effluent concentrations of BOD, COD, and TSS will be exceeded. Table 8 clearly indicates that for the main parameters, COD, BOD and TSS, the CV was low, indicating low variability in plant performance. The value of this coefficient decreased as the level of treatment progressed, reaching very low values after tertiary treatment, which means that the tertiary treatment stage further stabilized the plant performance. These values are much lower than those reported by [26] for full-scale treatment plants using different treatment systems. This difference could be explained by the fact that the plant under study is new and still operating at its designed capacity.

3.4.2. Reliability analysis

Reliability refers to the percentage of time the expected effluent values from a WWTP meet the discharge limits set

Table 7
Standard limits set by KEPA and actual Kabd WWTP values

Parameter	Abbreviation	Unit	(KEPA) irrigation water standard	(Kabd contract) irrigation water standard	Kabd WWTP	Year	Standard satisfied
Temperature	Temp.	°C	–	45	28.11	2013	Yes
					28.82	2014	Yes
					28.41	2015	Yes
					28.09	2016	Yes
pH	pH	–	6.5–8.5	6.5–8	7.16	2013	Yes
					7	2014	Yes
					6.95	2015	Yes
					6.89	2016	Yes
Biochemical oxygen demand	BOD_5 (5 d, 20°C)	mg/L	20	10	3.65	2013	Yes
					5.01	2014	Yes
					4.69	2015	Yes
					5.39	2016	Yes
Chemical oxygen demand	COD	mg/L	100	100	19.61	2013	Yes
					28.13	2014	Yes
					23.24	2015	Yes
					24.09	2016	Yes
Oil & grease	–	mg/L	5	5	0.28	2013	Yes
					0.46	2014	Yes
					1.82	2015	Yes
					2.13	2016	Yes
Conductivity	–	µs/cm	–	2,000	1,165.41	2013	Yes
					1,459.33	2014	Yes
					1,445.75	2015	Yes
					1,394.57	2016	Yes
Total dissolved solids	TDS	mg/L	–	1,500	955.27	2013	Yes
					958.57	2014	Yes
					749.32	2015	Yes
					608.54	2016	Yes
Total suspended solids	TSS	mg/L	15	10	4.62	2013	Yes
					6.46	2014	Yes
					5.88	2015	Yes
					5.63	2016	Yes
Phosphate	PO_4	mg/L	30	25	1.71	2013	Yes
					1.99	2014	Yes
					1.83	2015	Yes
					2.44	2016	Yes
Ammonia	NH_3–N	mg/L	15	15	2.6	2013	Yes
					3.5	2014	Yes
					3.75	2015	Yes
					6.51	2016	Yes
Nitrate–nitrogen	NO_3–N	mg/L	35	20	6.16	2013	Yes
					3.28	2014	Yes
					3.26	2015	Yes
					6.21	2016	Yes
Turbidity	–	NTU	–	50	3.42	2013	Yes
					4.9	2014	Yes
					3.67	2015	Yes
					3.4	2016	Yes

(Continued)

Table 7 Continued

Parameter	Abbreviation	Unit	(KEPA) irrigation water standard	(Kabd contract) irrigation water standard	Kabd WWTP	Year	Standard satisfied
Dissolved oxygen	DO	mg/L	>2	–	2.78	2013	Yes
					3.29	2014	Yes
					3.98	2015	Yes
					4.7	2016	Yes
Total coliforms	–	MPN/100 mL	400	400	6.89	2013	Yes
					2.76	2014	Yes
					4.89	2015	Yes
					3.34	2016	Yes
Fecal coliforms	–	MPN/100 mL	20	0	0.25	2013	No
					0.92	2014	No
					1.49	2015	No
					0.52	2016	No
Salmonella	–	MPN/100 mL	–	0	2.64	2013	No
					1.13	2014	No
					0.87	2015	No
					0.44	2016	No

Table 8
Mean and coefficient of variation (CV) of plant performance data

Parameter	COD			BOD			TSS		
	Raw	Sec.	Ter.	Raw	Sec.	Ter.	Raw	Sec.	Ter.
Mean, (mg/L)	598.1	38.1	10.5	96.2	8.36	5.44	163.22	8.67	5.69
Standard deviation, (mg/L)	108.256	5.677	1.449	15.58	1.137	0.671	20.561	0.671	0.360
CV	0.181	0.149	0.138	0.162	0.136	0.123	0.126	0.077	0.063
COR			0.78			0.81			0.92

by environmental authorities [27]. The reliability can be determined by using the coefficient of reliability (COR), which can be calculated from the following equation [26]:

$$\mathrm{COR} = \sqrt{\mathrm{CV2}} + 1x\,\exp\left\{-Z_{1-\alpha}\sqrt{\ln\left(\mathrm{CV2}+1\right)}\right\} \quad (2)$$

where CV is the coefficient of variation and α is the probability of failure of meeting the standards. $Z_{1-\alpha}$ is the standardized normal variate obtained from standard normal variate tables [26,27]. Following the method outlined by [26], the COR values were calculated as presented in Table 8 at a level of reliability of 95%. For the three main parameters of interest, that is, COD, BOD and TSS, the CV values obtained were much lower than 1.0. For the same level of reliability of 95%, a lower CV value leads to a higher COR value, which means more stable operating conditions and compliance with the effluent discharge standards for reuse in irrigation.

4. Conclusion

This study was carried out to identify seasonal variations in parameters to promote the optimization of the operational conditions and performance of WWTPs. Thus, the understanding and interpretation of parameter values occurring in different periods of the year will help define the treatment process and operating conditions. For instance, during high-BOD seasons, the airflow in the nitrification process should be increased to achieve high performance. However, the results obtained in this study indicate that variations in water temperature affect the biological treatment process and microbial population. Physicochemical characteristics exhibited slight changes with respect to seasonality. For the microbial parameters investigated, an effect of seasonal variations was observed. Generally, the observations showed that microbial parameters in the wastewater inflow and effluent retain better performance in spring. The removal efficiency of the biological process is better in fall than in summer. For the main parameters, COD, BOD and TSS, the CV was low, indicating low variability in plant performance. The value of this coefficient decreased as the level of treatment progressed, reaching very low values after tertiary treatment, which shows the role of tertiary treatment in achieving stable plant effluent quality. However, despite the seasonal variations observed in the parameters, the WWTP showed consistent performance, allowing the usage of effluent discharge in several applications, for example, irrigation, in compliance with relevant standards.

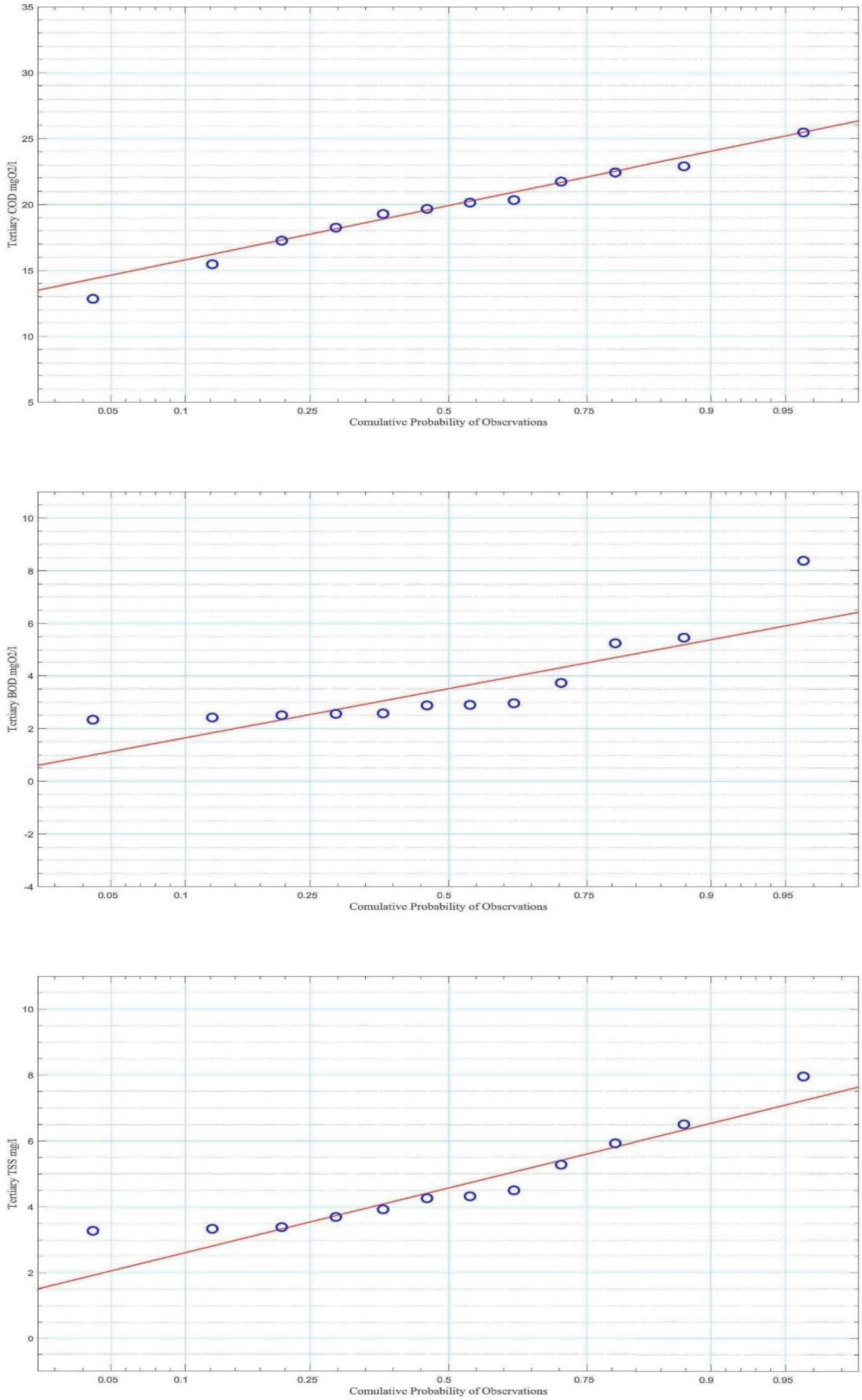

Fig. 9. Probability plots of tertiary-treated effluent quality parameters.

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Supporting information

Table S1
Linear regression analysis for physicochemical parameters

Parameter	R^2	Coefficients		Significance
TSS	0.331	Constant	88.604	0.000
		Temperature	–0.045	0.328
		pH	0.625	0.352
		Conductivity	–5.172E-6	0.996
		VSS	–0.012	0.143
		TSS	0.019	0.000
		COD	0.000	0.723
		BOD_5	0.006	0.007
		O&G	0.012	0.193
		$N–NH_3$	0.024	0.470
		PO_4	–0.050	0.118
VSS	0.137	Constant	97.717	0.000
		Temperature	0.018	0.891
		pH	–1.226	0.532
		Conductivity	2.236E-5	0.994
		VSS	0.036	0.136
		TSS	–0.019	0.174
		COD	0.005	0.125
		BOD_5	0.010	0.106
		O&G	0.016	0.554
		$N–NH_3$	0.008	0.938
		PO_4	0.098	0.290
COD	0.416	Constant	93.951	0.000
		Temperature	0.003	0.963
		pH	–0.520	0.549
		Conductivity	–0.001	0.273
		VSS	0.005	0.641
		TSS	–0.009	0.120
		COD	0.007	0.000
		BOD_5	0.009	0.001
		O&G	0.016	0.200
		$N–NH_3$	0.064	0.135
		PO_4	–0.025	0.542
BOD_5	0.406	Constant	96.613	0.000
		Temperature	–0.054	0.064
		pH	0.243	0.564
		Conductivity	–0.001	0.293
		VSS	0.002	0.639
		TSS	–0.006	0.038
		COD	0.001	0.386
		BOD_5	0.007	0.000
		O&G	0.002	0.729
		$N–NH_3$	0.045	0.033
		PO_4	–0.018	0.352

(Continued)

Table S1 Continued

Parameter	R^2	Coefficients		Significance
O&G	0.216	Constant	72.035	0.001
		Temperature	0.338	0.108
		pH	3.811	0.214
		Conductivity	–0.009	0.057
		VSS	–0.063	0.090
		TSS	0.051	0.020
		COD	–0.007	0.161
		BOD_5	–0.013	0.208
		O&G	0.066	0.125
		$N–NH_3$	0.014	0.926
		PO_4	0.041	0.776
$N–NH_3$	0.105	Constant	96.309	0.108
		Temperature	–0.305	0.597
		pH	–0.331	0.969
		Conductivity	–0.011	0.379
		VSS	–0.144	0.160
		TSS	0.091	0.129
		COD	0.003	0.829
		BOD_5	0.021	0.452
		O&G	–0.099	0.398
		$N–NH_3$	–0.069	0.870
		PO_4	–0.005	0.991
PO_4	0.306	Constant	119.918	0.000
		Temperature	–0.507	0.040
		pH	–3.808	0.287
		Conductivity	–0.009	0.077
		VSS	–0.078	0.075
		TSS	0.015	0.556
		COD	0.009	0.133
		BOD_5	–0.003	0.791
		O&G	0.065	0.192
		$N–NH_3$	0.229	0.197
		PO_4	0.546	0.002

Table S2
Linear regression analysis for microbial parameters

Parameter	R^2	Coefficients		Significance
Total coliform	0.021	Total coliform	100.000	0.000
		Fecal coliform	3.570E-17	0.306
		Salmonella	–9.339E-18	0.981
		Fecal streptococci	1.149E-15	0.587
		Fungi	–6.299E-15	0.219
Fecal coliform	0.014	Total coliform	100.000	0.000
		Fecal coliform	1.469E-16	0.580
		Salmonella	3.005E-15	0.319
		Fecal streptococci	–2.674E-15	0.868
		Fungi	–3.066E-15	0.937
Fecal streptococci	0.139	Total coliform	100.000	0.000
		Fecal coliform	–8.345E-15	0.170
		Salmonella	1.416E-13	0.041
		Fecal streptococci	–6.203E-13	0.093
		Fungi	–3.499E-12	0.000
Salmonella	0.024	Total coliform	100.000	0.000
		Fecal coliform	3.057E-16	0.905
		Salmonella	1.160E-14	0.689
		Fecal streptococci	2.453E-14	0.874
		Fungi	–7.033E-13	0.062
Fungi	0.182	Total coliform	99.998	0.000
		Fecal coliform	–1.488E-13	0.243
		Salmonella	8.875E-13	0.539
		Fecal streptococci	–1.307E-11	0.092
		Fungi	9.529E-12	0.610