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Statistical correlation analysis and energy consumption of electrically-enhanced membrane bioreactor for wastewater treatment

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ABSTRACT

In this paper, the dependence of total dissolved solids (TDS) and turbidity of influent and effluent streams on the properties of a submerged membrane bioreactor integrated with electrokinetic treatment for raw municipal wastewater treatment was investigated. The relationship between the mixed liquor suspended solids (MLSS) and other reactor properties was also studied. Furthermore, the specific energy consumption of the set-up and cost of water treatment were estimated. It was observed that soluble phosphorus, pH, and carbon oxygen demand (COD) were mostly correlated with the TDS of the feed while the effluent TDS was more sensitive to total nitrogen (TN), pH, ammonium-nitrogen (NH_4^+–N) and soluble fraction of COD. The turbidity of the wastewater and treated effluent correlated well with the nitrogen species while MLSS showed high correlation with aluminum phosphate concentration. The multiple R, R^2 and adjusted R^2 obtained for the MLSS regression analysis were 0.9, 0.9 and 0.9, respectively. The system's specific energy consumption and cost were obtained as 0.87 kWhm^{-3} and USD 0.06 m^{-3}, respectively. This study shows the correlation or relationship between the measured properties in wastewater treatment.

Keywords: Membrane bioreactor; Electrokinetic treatment; Statistical analysis; Wastewater treatment; Energy; Cost

1. Introduction

As population is increasing in most parts of the world coupled with rise in industrial activities and agricultural production, the use of water for drinking, agriculture, irrigation, district cooling and industrial applications is increasing at an alarming rate [1,2]. There is still limited supply of usable water in the world [3–6]. Therefore, there is need to devise alternative treatment procedures for water production and ensure that the produced water meets the quality and cost required for the desired application. The reuse of wastewater for potable and non-potable uses is becoming increasingly important because of the need to reduce depletion of fresh water resources and mitigate the scarcity of water [7]. Many treatment technologies have been used in the past and new methods are currently being devised. The activated sludge process (ASP) is the conventional treatment approach and this method involves the use of microorganisms to remove wastes such as organic matter [8–13]. The use of ASPs has also found applications in the biological removal of nitrogen and phosphorus in domestic, commercial and industrial wastewater [14]. Membrane bioreactor (MBR) technology, which consists of a semi-permeable membrane added to the conventional biological treatment to aid filtration of water and retention of biomass in the treatment reactor, is another applied technique for reclamation of wastewater [15–22]. Wastewater treatment through the use of MBRs has been shown to offer comparative advantages over conventional activated sludge systems [23,24]. Since MBRs allow the retention of microorganisms or biomass in the treatment reactor, MBRs have the benefits of higher concentration of biological species in the reactor for treatment and better treated effluent quality [25,26]. The membrane in the MBR can be submerged inside

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the reactor or used externally in side stream applications. The submerged MBR, in particular, offers the advantages of low energy consumption, low pumping costs, small environmental footprint, and feed-forward control of oxygen demand [27–29].

The reactor used in this study was an electrically-enhanced MBR, a unit which combines biological degradation, membrane filtration and electrocoagulation of the wastewater pollutants in an integrated set-up. The combination of these processes by Elektorowicz et al. [30] in "submerged membrane electro-bioreactor (SMEBR)" resulted to higher effluent quality, when compared with MBR or the same system without electrodes. The SMEBR showed 95, 70–80, and 97% removal efficiencies of carbon oxygen demand (COD), ammonium as nitrogen (NH_4^+–N), and orthophosphates as phosphorus (PO_4^{3-}–P), respectively from synthetic wastewater. In a related work by Bani-Melhem and Elektorowicz [31], the hybrid treatment technology was shown to enhance removal of COD and PO_4^{3-}–P to 96 and 98%, respectively from synthetic wastewater using intermittent direct current (DC) with an operational mode of 15 min ON: 45 min OFF. Also, in the MBR incorporated with ~ 0.2 V/cm electric field (EMBR) using copper wire cathode and stainless steel mesh anode, Liu et al. [32] observed enhanced sludge properties (in terms of reduction in sludge volume index and improvement in compactness) and better removal of soluble COD component from synthetic municipal wastewater, as compared to the system without electric field. Other studies have also shown the positive impacts of electric field on the treatment properties of sludge from wastewater treatment [16–33,34].

The electrically-enhanced MBR has given interesting results in terms of pollutants' removal from wastewater [27,35,36]. However, in order to determine the quality of effluent and characteristics of wastewater in wastewater treatment, many components need to be determined leading to high cost of operation and complexity of quality measurement. Therefore, it is necessary to reduce the predicaments associated with measurements by studying some lumped components and the individual components on which they are dependent. However, lumped properties are not sufficient to ensure reduction of the cost of testing and measurements under real operating conditions because many regulatory standards require full characterization of the wastewater, TDS and turbidity provide the operator or engineer with first-hand information necessary to avoid process disruptions and ensure predictive process design and control. Therefore, the knowledge of the relationships between these lumped properties and individual components might influence the overall cost of treated water production. In this study, non-mechanistic models were used to describe these composite components and properties such as total dissolved solids (TDS), mixed liquor suspended solids (MLSS) and turbidity because of the huge complexity that normally results from attempts to use differential equations to model their removal from wastewater. Since these components and properties are functions of a pool of other substances and properties, it is highly necessary to find out which components are more sensitive to these lumped components. Therefore, the dependence of TDS and turbidity of influent and effluent streams on the other system properties in a submerged membrane bioprocess reactor hybridized with electrokinetic phenomenon for raw municipal wastewater reclamation was investigated. TDS and turbidity are important water quality indicators, particularly for the effluent, because these properties provide a firsthand face-value assessment of the quality of the produced water in terms of the appearance and dissolved solids present. For example, the TDS and turbidity of treated water for wholesome applications, according to standards set by the United States' Environmental Protection Agency (U.S. EPA) must not exceed 500 ppm and 0.3–1.0 NTU, respectively [37]. The relationship between MLSS and the reactor content was also studied. This provided an opportunity to estimate the values of the properties and variables of concern from other system variables, instead of duplicating laboratory tests.

Some studies had been carried out in the past to find the relationship between some properties of wastewater and treated effluent in order to reduce measurement constraints and provide adequate basis for recommending treated water for different applications [38,39]. However, there are limited literatures linking TDS and turbidity with other wastewater treatment system's properties. No previous study investigating the relationship between these components was found for the hybrid processes considered in this paper. The statistical analysis of the MLSS was also carried out in this study to determine the properties on which MLSS in the hybrid reactor would mostly be dependent upon. Furthermore, the cost required to run the set-up was estimated by taking into account the specific energy consumption of the system.

2. Materials and methods

The reactor is a rectangular reactor made up of polycarbonate sheets. The fresh activated sludge was collected from the MBR plant at Masdar City, Abu Dhabi, United Arab Emirates. The electrically-enhanced MBR is shown in Fig. 1. The total effective volume of the reactor was 22.5 L. Unscreened variable-feed raw municipal wastewater was fed to the activated sludge. The characteristics of the wastewater are shown in Table 1. The food-to-microorganisms ratio used was 0.6. KUBOTA flat sheet 0.4 µm microfiltration membrane, having an effective surface area of 0.11 m^2, was inserted at the centre of the reactor and submerged in the mixed liquor. A continuously stirred system is ensured by aerating the reactor content and pumping the wastewater and effluent into and out of the mixed liquor. A hydraulic retention time of 13.5 h and sludge retention time of 10 d were maintained. Pumping was carried out using Cole-Parmer's MasterFlex peristaltic pumps while mixing was aided by passage of air through fine bubble diffusers attached to the base of the reactor.

The measured components were chemical oxygen demand (COD), soluble COD (CODs), biodegradable soluble COD (Ss), inert particulate COD (Xps), nitrate as nitrate-nitrogen (NO_3^-–N), ammonia as ammonium-nitrogen (NH_4^+–N), total nitrogen (TN), orthophosphate or soluble phosphate (PO_4^{3-}–P), aluminum phosphate (MeP), total phosphorus (TP), total iron (Fe), total nickel (Ni), total chromium (Cr), and aluminum hydroxide as $Al(OH)_3$. The experimental samples were first prepared using the wastewater carbonaceous content characterization methods before CODs, Ss, and Xps could be determined from the

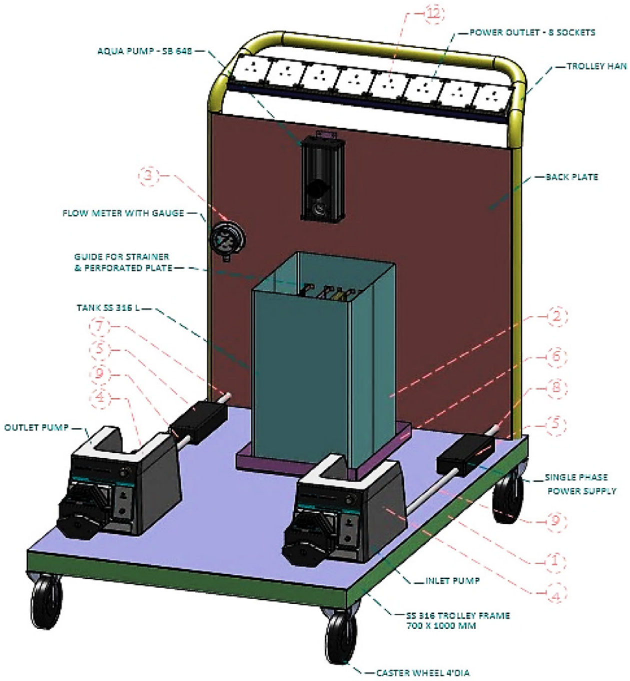

Fig. 1. The electrically-enhanced membrane bioreactor. 1 - Trolley assay, 2 - Tank assay, 3 - Flow meter, 4 – Pump, 5 - Power supply, 6 - Containment tray, 7 - Wire power – left, 8 - Wire power, 9 - Wire to pump, 10 - Drain tube, 11 - AQUA pump, 12 - Power socket.

vials [40,41]. TDS and pH were measured by using conductivity and pH probes connected to the DO meter while turbidity was determined through the use of HACH 2100AN Turbidimeter. MLSS and mixed liquor volatile suspended solids (MLVSS) in the samples were also measured using standard methods [42].

The flow of influent raw wastewater was maintained at 40 L d^{-1} and a constant flux of 15.2 L m^{-2} h^{-1} of effluent was ensured. The diffusers were connected to Cole Parmer's 150 mm correlated air flow meter EW-03217-30 from where the air flow rate was adjusted. Biodegradation of the wastewater content was ensured by the biological species in the mixed liquor while the filtration of water from the mixed liquor was aided by the membrane. Apart from the membrane bioprocess, a third process – electrocoagulation – was added to the hybrid system. Electrocoagulation of the colloids and non-biodegradable species in the wastewater was ensured by vertical electrodes inserted inside the reactor. The anode, made up of aluminium sheet, and a cathode made up of stainless steel, were placed in the reactor and connected to DC power supply. Fine bubbles of flow rate 2.3 L min^{-1} were passed to the bulk mixed liquor to maintain the dissolved oxygen (DO) above 2 mg L^{-1} for biological activity but the air flow rate near the membrane surface was maintained at 4.6 L min^{-1} for coarse bubble scouring in order to prevent membrane fouling. DO was measured using HQ40d Multi DO meter. A current density of 15 A m^{-2} was maintained in the system. Intermittency of current was ensured in order to control the discharge of electrocoagulants into the mixed liquor by connecting the power supply to a timer maintained at 5 min: 15 min ON: OFF mode. Some

Table 1
Characteristics of the raw municipal wastewater

Parameter	Range
TDS (mg/L)	597 ± 146.6
Turbidity	78 ± 31.6
pH	7.2 ± 0.6
COD (mg/L)	849.6 ± 217.1
CODs (mg/L)	306.8 ± 78.4
Ss (mg/L)	209.1 ± 53.4
Xps (mg/L)	490.1 ± 125.2
NO_3^-–N (mg/L)	0.61 ± 0.2
NH_4^+–N (mg/L)	93.2 ± 33.8
TN (mg/L)	120.7 ± 29.4
PO_4^{3-}–P (mg/L)	6.7 ± 2.1
MeP (mg/L)	0.11 ± 0.03
TP (mg/L)	8.4 ± 2.6
Fe (mg/L)	1.8 ± 1.1
Ni (mg/L)	0.7 ± 0.3
Cr (mg/L)	0.15 ± 0.1
$Al(OH)_3$ (mg/L)	0.8 ± 0.3

wastewater and treated effluent components were measured using HACH vials. The vials were specially packaged cuvettes with distinctive barcodes consisting of reagents through which components were detected using spectrophotometric chemistries. Specifically, a HACH LANGE DR3900 spectrophotometer using radio frequency identification technology (RFID) technology was used to read the concentrations of these components from the cuvettes.

The integrated processes were allowed to run for 60 d. Measurements of properties were carried out at regular intervals during this period. Multiple regression analysis was then carried out to obtain the regression equation linking each dependent variable to other components having high correlation with the variable. Confidence interval of 95% was employed in all cases. The energy cost of the hybrid system was carried out using the specific energy consumption. The costs obtained in this study may vary elsewhere, especially in locations where the unit cost of electricity is much higher. The geographical reference used was Abu Dhabi, United Arab Emirates.

3. Results and discussion

3.1. Dependence of feed and effluent TDS on other state variables

The TDS and turbidity of influent and effluent were not modelled mechanistically because of the complexity involved in converting the units of dissolved components to TDS and turbidity, since the actual chemical compounds that made up the dissolved components in the municipal wastewater and effluent were not completely known. The experimental values of TDS and turbidity of the wastewater and treated effluent are shown in Fig. 2a and 2b.

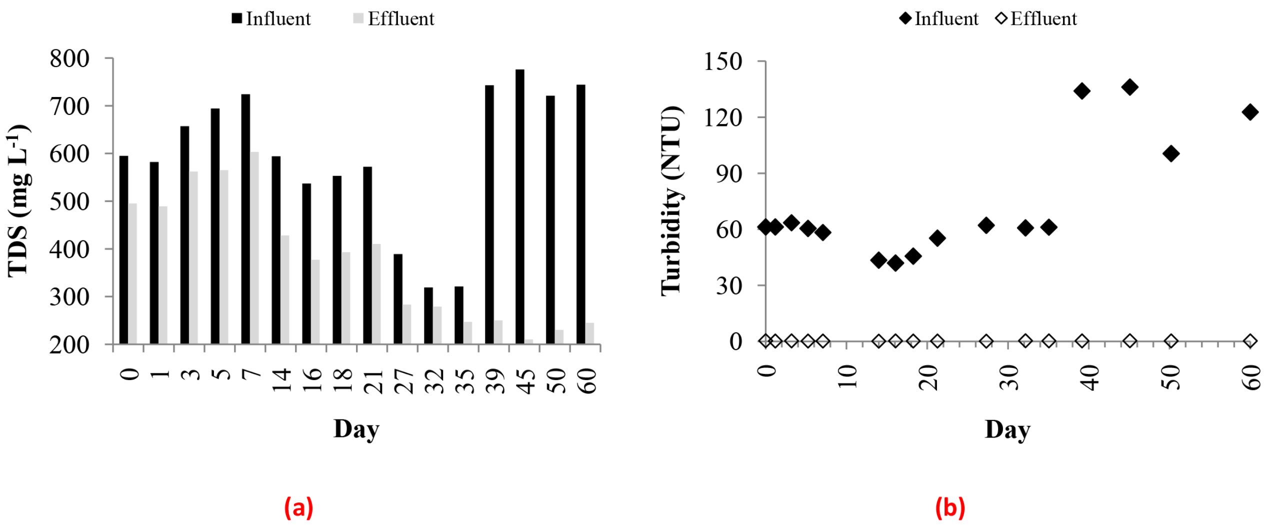

Fig. 2. Experimental values of (a) TDS; and (b) turbidity of wastewater and treated effluent.

The correlation coefficients between TDS and feed compositions were first obtained. Table 2 shows how the dissolved substances and properties in the feed correlate with the TDS.

It was observed that soluble phosphorus and pH shows the highest positive correlation while COD shows the highest negative correlation with the TDS of the municipal wastewater. The high correlation coefficients associated with some variables reveal that TDS depend more on these variables than other feed components. However, among the other variables, the dependence of TDS on nitrate was found to be very low. The correlation statistics show the feed compositions that needed to be controlled or given more attention in order to have the desired influent TDS into the mixed liquor. The filtering out of the independent variables that showed low correlation with TDS resulted into lower regression residuals. TN was excluded as an independent variable in the regression analysis and only NH_4^+–N was included because NH_4^+–N showed higher positive correlation with TDS than TN, although the correlation coefficients of both were close.

TN was excluded to reduce the regression errors or residuals by reducing the number of independent variables or removing redundant variables. This might be attributed to the fact that NH_4^+–N accounts for most of the soluble fraction of nitrogen in the wastewater. However, this is not true for the treated effluent because most of the NH_4^+–N would have been biodegraded to nitrogen gas. The result of this regression analysis and the coefficients of determination of the regression statistics are provided in Table 3.

The regression statistics obtained in the form of R – coefficient of determination – show the best regression fit and rationality of the regression analysis. The multiple R regression statistics obtained was 0.8 but the R^2 and adjusted R^2 coefficients were lower. The lower adjusted R^2 obtained was as a result of the uncertainty in feed quality, since raw wastewater feed obtained directly from the point of discharge was used for this study. The plot of the various observations of the influent TDS against the predicted values and resulting regression residuals is provided in Fig. 3. It was observed that there was close agreement between the measured TDS and predicted TDS at the initial stages of the experiment but there was more disparity as the integrated processes progressed. This might be as a result of the varying concentrations of each of the components in the municipal wastewater feed into the system.

The source of wastewater, geographical location and the physical condition of the influent in terms of temperature

Table 2
Correlation coefficients between wastewater TDS and other properties

	TDS	pH	NO_3^-–N	TN	CODs	COD	NH_4^+–N	PO_4^{3-}–P
TDS	1.0							
pH	0.4	1.0						
NO_3^-–N	0.0	–0.5	1.0					
TN	0.3	0.8	–0.6	1.0				
CODs	–0.3	–0.4	0.2	–0.6	1.0			
COD	–0.3	–0.4	0.2	–0.6	1.0	1.0		
NH_4^+–N	0.4	0.8	–0.6	1.0	–0.7	–0.7	1.0	
PO_4^{3-}–P	0.7	0.2	0.0	0.3	–0.5	–0.5	0.4	1.0

Table 3
Regression statistics of wastewater TDS as correlated to other properties

	Coefficients	Coefficient of determination	Value
Regression constant	−491.3	Multiple R	0.8
CODs	0.3	R^2	0.6
NH_4^+–N	−0.4	Adjusted R^2	0.5
PO_4^{3-}–P	55.7		
pH	90.9		

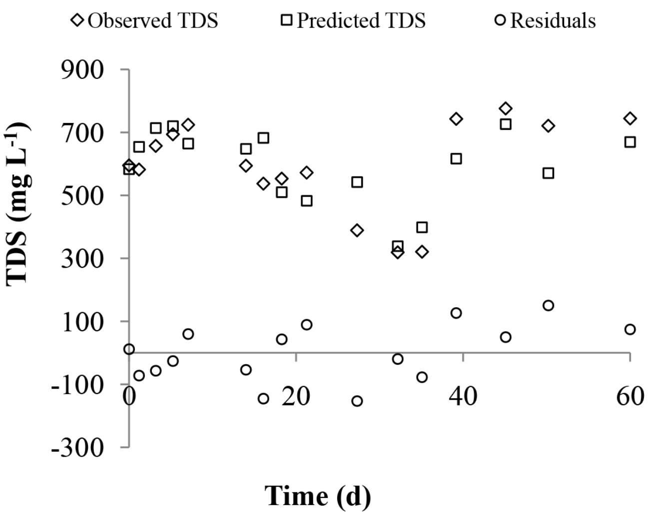

Fig. 3. Predicted and observed values of raw wastewater TDS.

and pH will alter the statistical dependence of a lumped property on other feed's variables for each specific application. However, the results presented here provide a basis for the estimation of the statistical dependence of the variables of concern provided the data for each specific application is known. In addition, all wastewaters can be broadly classified as: high-strength, low-strength, and medium-strength wastewater. This classification is applicable for all wastewater types and can be used to differentiate between the wastewater in different geographical locations. The wastewater used in this work is a medium-strength wastewater. Meanwhile, if the wastewaters in two different locations fall under the same category, it is safe to conclude that they are fairly similar in strength. Therefore, the findings in this work are not confined to wastewater treatment in Abu Dhabi. These findings are fairly applicable to all medium strength wastewaters in different locations since the compositions of pollutants in these wastewaters would fall under the same broad ranges. Although exact similarities in results would never be obtained while using different forms of medium-strength wastewater, this work is statistical modeling for prediction purposes and it is expected that a considerable degree of closeness would be achieved. In the same manner, the correlation statistics for the dependence of effluent TDS on other components were determined. The effluent TDS was observed to be more sensitive to TN, pH, NH_4^+–N and CODs. To obtain the regression equation, NH_4^+–N was excluded and TN was selected because both variables showed almost the same correlation coefficient. However, as also observed with the influent, effluent TDS is poorly correlated with NO_3^-–N. Rather than measuring several parameters that show similar dependence (i.e. ammonia, TN etc.), it would be statistically appropriate to select only one of these parameters to reduce the regression errors. Since TN represents all nitrogen fractions including ammonia and nitrite-nitrate, and shows almost the same level of significance as these fractions, TN was best suited as the representative dependent variable for the nitrogen fractions here. NH_4^+–N and NO_3^-–N were only investigated to see whether their relationships with TDS would differ considerably from that of TN. The correlation coefficients of these solutes with effluent TDS are provided in Table 4.

The results of the multiple regression analysis of effluent TDS and other effluent properties, and the fitness of the observed data to the regression model are presented in Table 5. Higher coefficients of determination were obtained for the correlation of effluent TDS with other treatment properties as compared to the values obtained for wastewater TDS. The multiple R, R^2 and adjusted R^2 values obtained were 0.8, 0.7, and 0.6 as compared to 0.8, 0.6, and 0.5 respectively obtained for the correlations involving wastewater TDS. To a large extent, the wastewater consists of more pollutants than the treated effluent. More specifically, in order to carry out a regression analysis for the wastewater, more independent variables would have to be considered. Some of these pollutants are correlated to each other because, in many cases, they are fractions of a composite. A rule of thumb in regression analysis is that, as the number of redundant independent variables increases, the standard error of the coefficients of such variables would also increase. This error would results from bias and uncertainty that would

Table 4
Correlation coefficients between effluent TDS and other properties

	TDS	pH	NO_3^-–N	TN	CODs	NH_4^+–N	PO_4^{3-}–P
TDS	1.0						
pH	0.7	1.0					
NO_3^-–N	0.0	0.1	1.0				
TN	0.8	0.7	0.0	1.0			
CODs	−0.2	−0.6	0.3	−0.3	1.0		
NH_4^+–N	0.7	0.7	−0.3	1.0	−0.4	1.0	
PO_4^{3-}–P	0.3	0.3	−0.1	0.6	−0.1	0.6	1.0

Table 5
Regression statistics of effluent TDS as correlated to other properties

	Regression coefficient	Coefficient of determination	Value
Regression constant	–1082.6	Multiple R	0.8
CODs	2.8	R^2	0.7
TN	4.3	Adjusted R^2	w
pH	161.7		

be added to the regression through redundancy. This is known as multicollinearity in statistics i.e. the regression becomes more difficult to analyze when more factors (most especially, redundant ones) are added [43,44]. On the other hand, treated effluent consists of mainly soluble components and it is easier to analyze the dependence of the properties of interest on the independent variables.

In the electrokinetic treatment of wastewater, the release of aluminum from the anode and the subsequent formation of aluminum hydroxide coagulants significantly aided the removal of PO_4^{3-} [35,27]. The amount of phosphates in the treated effluent was nearly reduced to zero by the bioelectrochemical treatment. PO_4^{3-} was mainly removed by electrocoagulation in the form of MeP in the mixed liquor and electrodeposition on the cathode [16,25,45,46]. However, CODs was still present in the treated effluent due to some recalcitrant trace organics and micropollutants which were not removed by the integrated processes. Therefore, for electrically enhanced MBR, it is more important to consider CODs than PO_4^{3-} for the analysis of the treated effluent. And since their correlation coefficients to TDS are close i.e. 2 & 3 (the negative sign only depicts inverse correlation), CODs has been selected in lieu of PO_4^{3-} to analyze the correlation between effluent TDS and other properties. The regression residuals are further shown from the plot of predicted and observed effluent TDS concentration, as presented in Fig. 4. A similar trend as that obtained for the influent was also observed for the regression analysis of effluent TDS with other variables. As the experiment proceeds towards the end in Fig. 4, the agreement between the observed and predicted effluent TDS widens. However, generally, the statistical prediction of effluent TDS was closer to the experimental results obtained, when compared with the statistical estimation of wastewater TDS. This might be as a result of other properties in wastewater on which TDS is dependent, since the raw municipal wastewater used contained a lot components, both known and unknown.

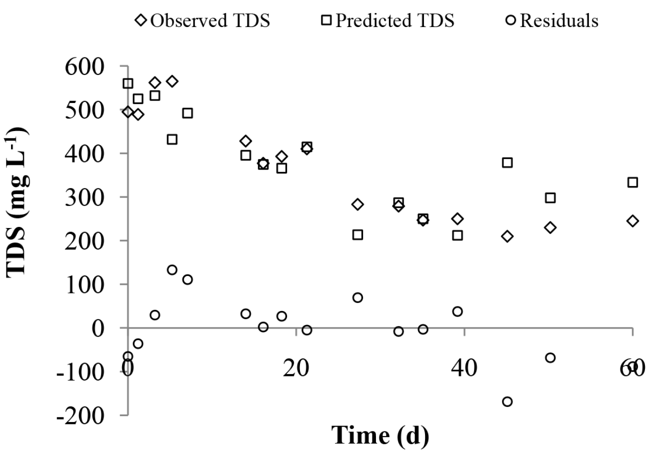

Fig. 4. Predicted and observed values of effluent TDS.

3.2. Dependence of feed and effluent turbidity on other state variables

Correlation analyses were also carried out to obtain the relationship between the turbidity and concentrations of feed water and effluent. Fig. 5 show how different compositions correlate with the turbidity of the wastewater and effluent. The coefficients of correlation obtained are presented in terms of positive and negative percentage correlations of turbidity with other properties of the wastewater and effluent. It was observed that the turbidity of wastewater was more sensitive to TN, Xps, and MLVSS and not sensitive to metal compositions. On the other hand, the turbidity of the effluent was more sensitive to the nitrogen species, PO_4^{3-}–P, and Fe content. The correlation coefficients relating the effluent turbidity to NH_4^+–N, PO_4^{3-}–P, TN and Fe are highest as compared to those of the other considered components, with relative values of 12, 12, 11 and –10% respectively.

The principle of light absorption or scattering in turbidity is mostly influenced by suspended particles [47,48]. The suspended particles in the wastewater also include its microbial content, which makes it necessary to characterize the biomass so that the response of wastewater turbidity to changes in biomass concentration under different operating conditions might be established. However, in this work, all experimental work was carried out at 20 ± 1°C and the biomass content was generally measured as MLVSS. There are different classes of microbes in wastewater including *E. Coli*, fecal coliforms, helminth and tapeworm ova, nematode eggs, etc. Since high correlation exists between MLVSS and wastewater turbidity (as shown in Fig. 5), the microbial characterization of wastewater would assist in determining the microbe that is significantly correlated to the effluent at a particular operating condition. Future work would be carried out in this area to investigate the dependence of wastewater turbidity on microbial fractions under different operating temperatures or climatic conditions (i.e. summer and winter).

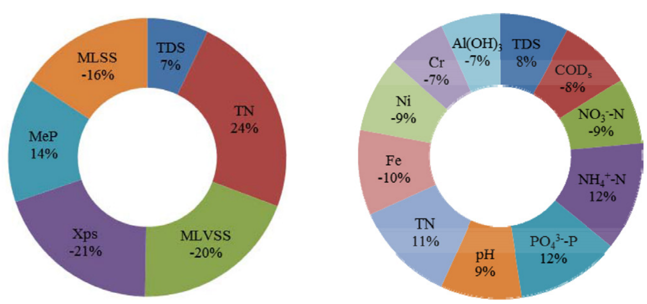

Fig. 5. Correlation coefficients relating turbidity of wastewater (left) and effluent (right) with other properties

3.3. Dependence of MLSS on other state variables

The statistical link of MLSS with the state variables in terms of coefficients of correlation indicates that the MLSS in the hybrid unit was highly dependent on MeP, MLVSS, TP and COD concentrations of the mixed liquor. MLSS was also observed as having low dependence on the particulate fraction of COD in the mixed liquor, Xps. Multiple regression analysis was then carried out to determine the regression equation relating the MLSS with other state variables. The results of this analysis and the fitness of the observed data to the regression model in terms of the coefficients of determination obtained are presented in the regression analysis in Table 6.

Higher values of regression statistics were obtained, indicating that there was high best fit between the dependent and independent variables for the regression equation obtained for MLSS. The multiple R, R^2 and adjusted R^2 obtained for the MLSS regression analysis were 0.9, 0.9 and 0.9 respectively. The regression residuals are further shown by the plot of predicted and observed mixed liquor concentration, as presented in Fig. 6. Lower residuals were obtained for the regression analysis of MLSS, as compared to the regression analysis of the dependence of TDS and turbidity on other variables. This might be due to the ease of measurement of many of the particulate substances which make up the MLSS by gravimetric methods, as opposed to the TDS and turbidity whose dependent variables had to be measured using several methods and instruments. As a result of this, systematic error might have affected the best fit of the dependence of TDS and turbidity on other variables. However, the number of dependent variables on which TDS and turbidity are dependent has been significantly reduced through the correlation analysis used in this study.

Table 6
Regression analysis of MLSS

	Regression coefficient	Coefficient of determination	Value
Regression constant	–356.5	Multiple R	0.9
MeP	0.1	R^2	0.9
TP	73.7	Adjusted R^2	0.9
COD	0.1		
MLVSS	1.2		

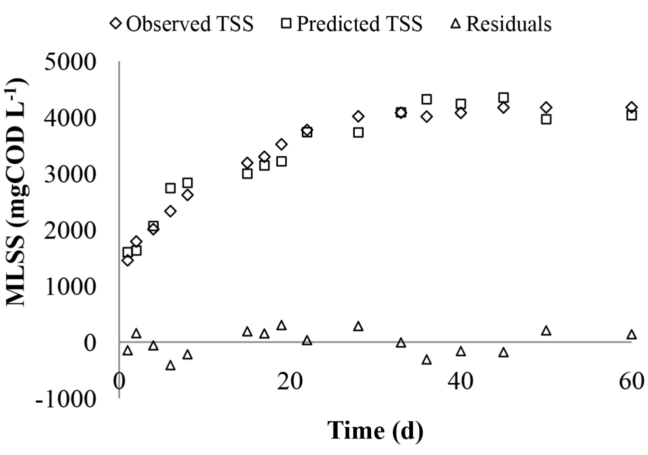

Fig. 6. Predicted vs observed values of MLSS.

3.4. Specific energy consumption of the hybrid system

The specific energy required by an electrically-enhanced membrane bioreactor is mainly responsible for its operating cost (and invariably the overall cost, since the contribution of operating cost to the overall cost is very significant in MBRs) [27]. For the studied system, the daily measurements of applied voltage and current across the reactor configuration were carried out. The fluctuations in the specific energy consumed by the system were then obtained by considering the daily volumetric flow rate of the treated effluent. Under a current of 0.83 A, specific energy consumption of 0.39–0.87 kWh m^{-3} was observed for this system. The specific energy consumed by the electrically-enhanced membrane bioreactor became stable after 30 d of operation, and this stability was monitored consistently afterwards (Fig. 7).

Despite the incorporation of electric field into the studied system, the specific energy consumption of the system is lower when compared with values obtained by Zhang et al. [49], Gil et al. [50], Bolzonella et al. [51], and Hasan et al. [27]. For immersed MBR systems, Zhang et al. [49] and Gil et al. [50] have obtained higher specific energy consumption of 6–8 and 4.9–6.1 kWhm^{-3}, respectively. Likewise, for full-scale MBR, a range of values of specific energy between 2.0 and 3.6 kWhm^{-3} was obtained by Bolzonella et al. [51]. In addition, in a pilot scale study of a submerged MBR incorporated with a single-pair cylindrical electrode configuration by Hasan et al. [27], higher values of electrical energy per unit volumetric flow rate were also obtained (1.1–1.6 kWhm^{-3}). Meanwhile, the very low specific electrical energy obtained for the double-pair vertical rectangular electrodes used in this study could be attributed to the enhanced current efficiency brought about by the double inter-electrode zone in the system. This zone was responsible for improved electrostatic effect. The zone was designed on both sides of the membrane using each electrode pair. The use of two

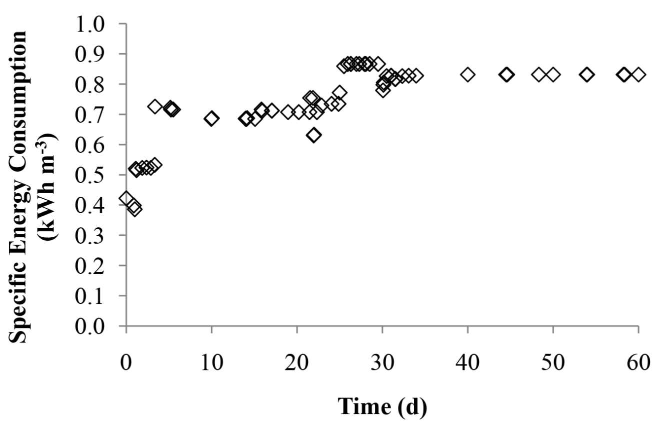

Fig. 7. Specific energy consumption of the electrically-enhanced membrane bioreactor.

pairs of electrodes improved the efficiency of electrostatic treatment through the reduction of longer electromigration distances and lessening of the more pronounced ionic cloud or ion-ion interaction that would have been experienced if a single pair of electrodes had been used (as it was in the case of Hasan et al.) [52].

In Abu Dhabi – the capital of the United Arab Emirates, for example, the average unit cost of electricity is 26 fils per kWh [53]. Therefore, the specific energy cost required by the studied electrically-enhanced MBR at steady state has been obtained as 21.6 fils or 0.06 USD m^{-3} of treated water. Meanwhile, it is worth noting that the capital cost of electrodes, capital and operating costs of other materials, and labor and maintenance cost have not been considered in this cost estimation. The total cost of treated effluent production from this system has not been carried out because of the scale of the system. The scale of a water-treatment system strongly determines the influence of capital cost on the specific cost of water production. Therefore, future work would be targeted at improving the scale of the system to pilot or demonstration scale before valid comparisons can be made between the total cost of water production from this system and other MBRs.

The specific energy and cost assessment carried out in this section is a preliminary estimation of the energy requirement of the system since energy consumption is a strong determinant of the total cost of water production from MBR systems. This cost estimation shows clearly that reduced energy cost would be obtained from the studied system as a result of the improved reactor configuration. The intermittency of direct current employed in the reactor has also been responsible for the energy cost reduction. Membrane fouling accounts for a sizeable proportion of the total cost of MBR operation [54]. However, MBR integrated with electrokinetic treatment would reduce membrane fouling and can lessen the frequency of membrane replacement [31,32,55]. Therefore, overall cost reduction due to elongation of membrane life would also be achieved by this system, when compared with ordinary MBRs without electrokinetic treatment. The specific energy requirement of the reactor can be further reduced if the system's operating conditions are further optimized.

4. Conclusions

In this study, the dependence of lumped water quality parameters such as TDS, turbidity, and MLSS on other water quality indicators was analysed in order to determine the individual water components that are most correlated to these variables. For the municipal wastewater for the selected geographical location and treated effluent, it can be concluded that there is high correlation between TDS and pH, and also high correlation between turbidity and the nitrogen species. Finally, MLSS shows high correlation with MLVSS and aluminium phosphate. The specific energy and cost of the hybrid system in a laboratory scale were also estimated. The system's specific energy consumption and cost were obtained as 0.87 $kWhm^{-3}$ and USD 0.06 m^{-3}, respectively. The specific energy consumed and its corresponding cost can be further reduced if the system's operating conditions are optimized and dependence of the measured parameters in the flows is taken into consideration. The savings in environment footprints by the system, when factored into the cost calculations, would also result in cost reduction. The water quality improvements offered by the integrated processes, when considered, would also improve the overall performance of the system [27,30]. Furthermore, the final cost of treated water after the distribution stage could also be reduced if the cost and complexities of measurements of individual components can be reduced through the examination of the relationships between components.

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