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Modeling the performance of a tannery common effluent treatment plant using artificial neural networks

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ABSTRACT

This paper demonstrates the application of artificial neural networks (ANNs) to model the performance of a common effluent treatment plant (CETP) treating tannery wastewater. The CETP treats the effluent from over 122 units located in the Pallavaram region of Tamil Nadu, India. A Levenberg–Marquardt feed forward back-propagation neural network with two hidden layers and 200 hidden neurons was used to develop the model. The raw and treated wastewater quality in terms of chemical oxygen demand, the total dissolved solids, the total suspended solids, chlorides, total alkalinity, and total hardness covering a period of 1 year was taken to construct the model. A total of 240 such sets of data were used for the training and validation of the network. The network was developed and trained using 200 of the 240 data sets. The fitness of the ANN model to predict the treated effluent quality and from that the plant performance was assessed on the basis of the correlation between the predicted values and the observed values, the normalized root mean square error, and the percentage averaged relative error. The trained model gave a correlation coefficient of 0.999, a normalized root mean square error of less than 0.2, and an averaged relative error of less than 18%. The accuracy of the model was further assessed for the prediction of the water quality of the remaining 40 data sets out of the total of 240 that had not been used for training the model. It was found that the model was able to predict the effluent wastewater quality with a correlation coefficient of 0.97. Thus the developed ANN model has been found to be suitable for assessing the performance of the CETP.

Keywords: Tannery wastewater treatment; Common effluent treatment plant; Artificial neural networks; Modeling; Performance assessment

1. Introduction

India produces about 13% of the world's leather, with close to 3 billion square feet of leather produced from about 700,000 tons of hides and skins processed in about 3,000 tanneries annually [1,2]. Cheap and abundant raw material, low-cost labor, and a thriving domestic and international market have ensured a sustained growth in the leather industry in India. However, tanneries are also among the most polluting and are classified as red category industries. The amount of solid, liquid, and gaseous waste produced from tanneries amounts to almost 50% by weight of the raw material processed [1]. Tanneries are water-intensive industries [3,4], and the wastewater generated is almost 90% of the water consumed [5]. The wastewater is typically described as yellowish brown to dark brown in color with generally high pH and extremely high levels of organic matter, suspended solids, dissolved solids, and inorganics such as nitrogenous compounds, chromium, sulfides and chlorides, sodium, and other salts, the levels of which vary with the type of process

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employed by the industry [3,5,6]. The presence of these components in high concentrations makes the tannery wastewater highly toxic and when discharged untreated into the environment, it has been found to cause not only an immediately discernable severe contamination of the environment [2], but the ill effects are also found to persist for a long time [7].

Tamil Nadu is the biggest hub of the tanneries in the country, housing 15 of the 113 tannery clusters in India comprising over half of the total units in the country [1,8]. Traditionally, vegetable tanning was employed in the region, however commercial compulsions in the 1970s caused a shift toward chrome tanning which had severe repercussions for the environment [9,10]. The discharge of untreated effluents and the resultant contamination of the groundwater and soil continued despite the stern warnings by the Tamil Nadu Pollution Control Board (TNPCB) in 1985 to treat industrial effluent prior to discharge. The resulting contamination of the soil and water was severe, turning tracks of agricultural land unfit for cultivation and drinking water wells brackish, rending most unpotable. The residents of the area also suffered from several health problems as a result of the untreated waste discharge. Even as some of the tannery owners acknowledged the pollution that was being caused, they pointed out to the logistical roadblocks that were delaying their efforts in setting up and implementing community wastewater treatment plants to handle the tannery effluents [10]. Taking cognizance of the dire situation, in 1989, the Planning Commission of the Government of India started a program for the setting up of common effluent treatment plants (CETPs) to treat tannery effluents, for which 25% of the capital cost was to be covered by the central government subsidy. The state government was to provide 25% and the rest was to be raised by the tanners and from the banks [9]. Several CETPs were set up in Tamil Nadu under this scheme.

The CETP at Pallavaram was the second to be set up under this scheme. Pallavaram is the second largest tannery cluster in Tamil Nadu, currently housing 126 units [8]. The CETP, named the Pallavaram Tanners Industrial Effluent Treatment Co. (PTIETC) was set up in 1995 with assistance from the United Nations Industrial Development Organization in collaboration with the TNPCB. The plant has a capacity of treating 3 million litres per day. Most of the 126 units that are served by the CETP are involved in converting semifinished wet blue or East India tanned leather to finished products. The CETP receives wastewater which has been pretreated for chromium, oil, and grease. As per the Chennai Environmental Management Company of Tanners' website [11], the plant was meeting TNPCB's discharge standards for all parameters except total dissolved solids (TDS), mainly due to chlorides and sulfates that were not getting removed by the treatment steps adopted in the plant. To meet the targets of TDS removal and zero-liquid discharge, the plant was upgraded and reverse osmosis (RO) units were installed. However, a TNPCB report of the monitoring of the CETPs in April 2017 has indicated that "ROA of treated trade effluent reveals that the parameters such as TDS, chlorides, SO_4, biochemical oxygen demand (BOD), chemical oxygen demand (COD) exceeds the standards prescribed by Board" [12].

This study presents the performance assessment of the PTIET CETP over a 1 year period spanning February 2016 to January 2017. An artificial neural network (ANN)-based model has also been developed based on the performance data to facilitate the prediction of the treated effluent water quality. There have been no studies found in literature on the application of ANNs to model tannery wastewater treatment plant performance. However, ANNs have been used for modeling syngas production from the gasification of dewatered tannery wastewater sludge [13], modeling the performance of a bench scale upflow anaerobic sludge digester for treating tannery wastewater [14], and for modeling the flux from a nanofiltration and reverse osmosis membrane filtration operation for treating leather plant effluent [15,16].

The application of ANN for modeling CETP performance has been demonstrated by Vyas et al [17–19]. ANN models of a CETP located in Bhopal, India, to treat industrial wastewater have been developed for the prediction of treated wastewater COD, given the CODs of the various wastewater streams received by the CETP and the equalization basin COD as input [17]. ANN models have also been constructed for the same CETP for the prediction of treated wastewater BOD and equalization basin BOD, when given the BODs of the various wastewater streams received by the CETP as input [18,19].

Thus this study is the first ever attempt at using ANNs to model a wastewater treatment plant for treating tannery wastewater. The study is also distinguished by the fact that it is the first ever study on the ANN modeling of a CETP to predict several water quality parameters of the treated wastewater. As the treatment plant is a CETP handling effluents from several industries, there is a large variation in total flow quality and quantity that is received by the plant. Even after equalization there is fluctuation in the quality of the wastewater that is handled by the treatment plant. In such a scenario, the modeling of the performance of the CETP can serve a very important role in predicting the effluent quality for a given influent quality ahead of time. If the effluent quality can be predicted for a given influent quality, in the event of the effluent quality not meeting discharge standards, appropriate interventions can be made to handle the wastewater so that it meets the discharge standards. Accordingly, an ANN model has been developed wherein six water quality parameters of the inlet wastewater—COD, TDS, the total suspended solids (TSS), chlorides (Cl), total alkalinity (TA), and total hardness (TH) is taken as the input, and the expected treated water quality in terms of the same water quality parameters is predicted.

2. PTIET tannery wastewater treatment plant

The raw effluent from the tannery cluster units is received from seven collection wells and one receiving sump and is pumped through mechanically cleaned screen into a grit chamber and collected in equalization tanks. In the tank submerged ejector aerators homogenize the effluent and completely oxidize the sulfides present in raw effluent. The equalized effluent is then pumped to a flash mixer where ~200–300 ppm of alum, 600 ppm of lime, and 1 ppm of anionic polyelectrolyte is added. Thereafter the effluent enters two clariflocullators, where the chemical sludge settles to the bottom. The overflow from the clariflocullator is treated biologically by an activated sludge process in two aeration tanks. The overflow from the aeration tanks with active biological solids is admitted into two secondary clarifiers. A portion of the settled sludge from the clarifiers is recycled back to the aeration tank to maintain an active biomass concentration. The remaining sludge portion is sent to a sludge thickener. The thickened caked sludge is sold as fertilizer [20]. The overflow from clarifiers is the treated effluent. As of April 2014, there was an RO plant installed to reduce the TDS and achieve zero-liquid discharge; however as per the plant personnel, it was functional for only a few months. Thus, the overflow from the clarifier does not undergo any further treatment and is discharged into Adyar River. The layout of the treatment steps is given in Fig. 1.

2.1. Wastewater quality and plant performance analysis

The quality of the raw wastewater received by the CETP and the treated effluent are routinely analyzed for pH, organic load in terms of COD and BOD, solids content in terms of TSS and TDS, TA, TH, and inorganics such as chlorides, sulfides, sulfates, total chromium, and oil and grease. For this study, the wastewater quality analysis of the influent to and effluent from the CETP was collected from the plant records covering February 2016–January 2017. The summary of the water quality data is presented in Table 1. As the CETP does not receive chrome tanning effluent from the tannery cluster, the total chromium levels are nil. Oil and grease is undetectable as the industries remove them prior to discharging the wastewater to the CETP.

The extent of treatment achieved in the reduction of the water quality parameters is presented in Fig. 2. The treated wastewater quality is compared against the Environment (Protection) Amendment Rules, 2015 [21] specified maximum

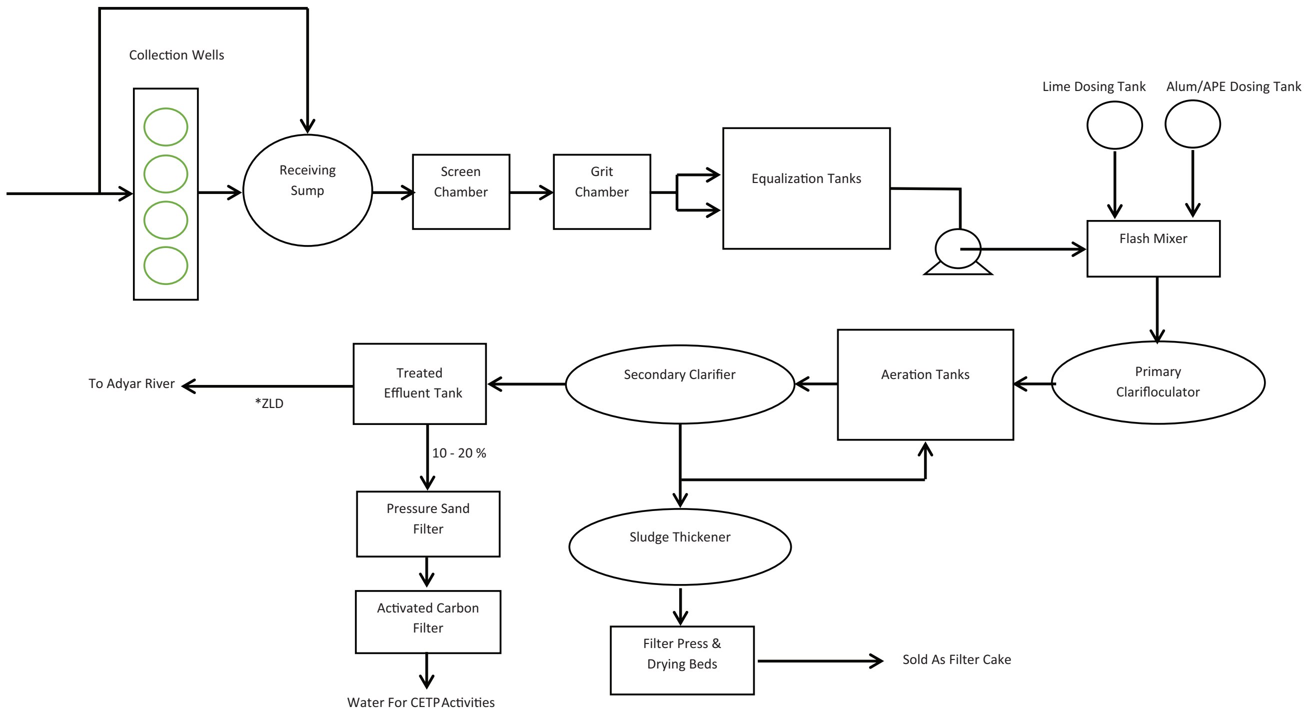

Fig. 1. Schematic of the PTIET wastewater treatment plant.

Table 1
Raw and treated wastewater quality

Water quality parameter	Raw influent quality		Treated wastewater quality	
	Range	Mean ± S.D.	Range	Mean ± S.D.
COD (ppm)	4,000–10,400	6,505 ± 1,463	300–1,800	661 ± 214
BOD (ppm)	1,000–2,000	1,440 ± 175	15–450	73 ± 64
TDS (ppm)	3,650–10,716	5,526 ± 929	1,380–7,620	5,676 ± 910
TSS (ppm)	740–5,260	2,055 ± 544	20–590	121 ± 67
Chlorides (ppm)	900–2,666	1,642 ± 195	900–1,933	1,602 ± 139
Total alkalinity (ppm)	60–1,080	505 ± 175	120–990	566 ± 132
Sulfides (ppm)	4–84	23 ± 12	0–24	0.65 ± 2
Sulfates (ppm)	–	–	60–357	160 ± 2
pH	4.3–7.9	6.9 ± 2	6.4–8.3	7.7 ± 0.3
Total hardness(ppm)	480–1,580	119 ± 177	700–1,590	1,055 ± 155

COD, chemical oxygen demand; BOD, biochemical oxygen demand; TDS, total dissolved solids; TSS, total suspended solids.

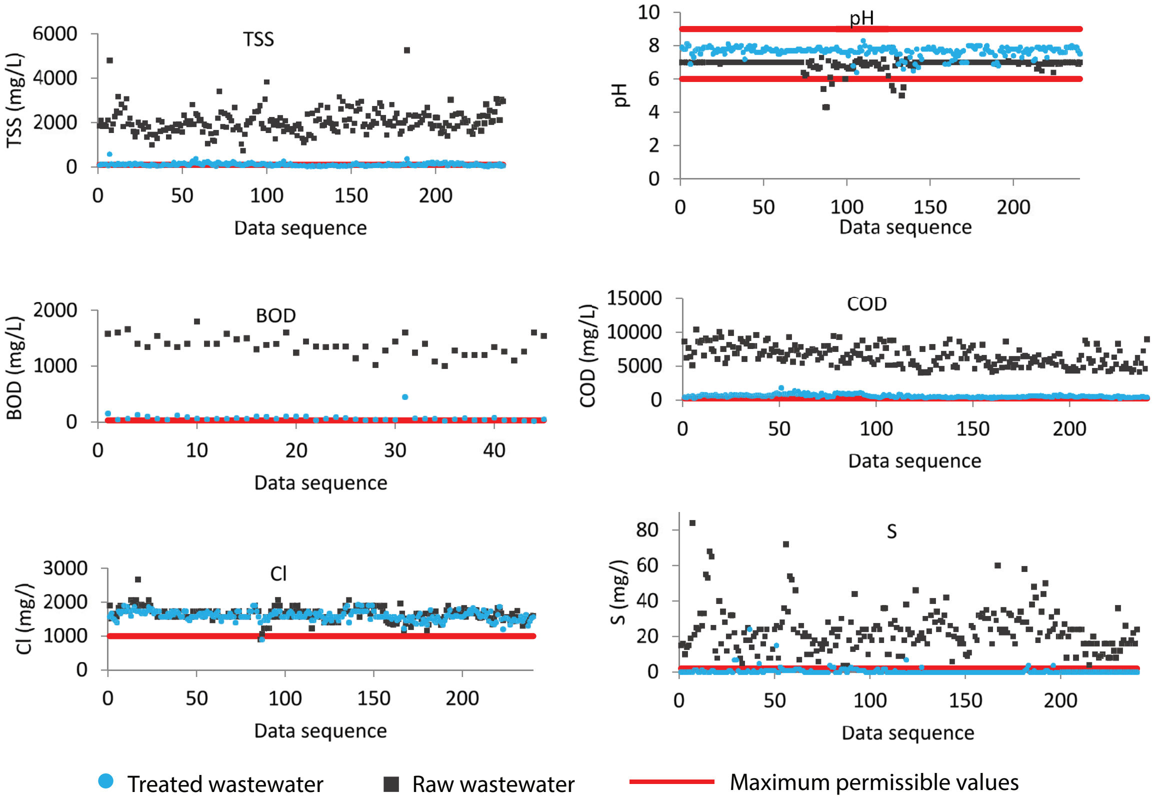

Fig. 2. Comparison of the raw and treated effluent wastewater quality against those prescribed by the Environment (Protection) Amendment Rules, 2015, for CETPs.

permissible values for discharge into inland surface waters. The standards [21] set discharge limits for CETPs in terms of general water quality parameters of pH, BOD, COD, TSS, and fixed dissolved solids; and industry-specific parameters. The parameters specific to tannery wastewater CETPs are sulfides, total chromium, oil and grease, and chlorides As the CETP does not receive wastewaters containing chromium and oil and grease, they are also absent in the treated wastewater and thus not included in the figure. The plant does not measure the fixed dissolved solids content of its wastewater hence this parameter could not be included here for comparison.

As may be seen from the figure, the treated wastewater does not meet the discharge standards for COD, BOD, and chlorides. The discharge standards are met inconsistently for TSS. The sulfide levels in the effluent are mostly zero, and only for less than 20 measurements out of the total of 240, the levels were found to be above the maximum permissible value of 2 mg/L. The pH was found to be within the specified range for over 97% of the measurements.

3. Modeling plant performance using ANNs

ANNs are one of the most widely used artificial intelligence techniques to model systems that are challenging to model analytically. ANNs are massive parallel computing intelligence techniques that mimic the structure and functioning of the biological neuron system. ANNs are basically complex yet organized and interconnected structures made up extremely large numbers of simple processors called neurons, arranged into layers. ANNs are increasingly being explored for making predictions and sense of complex nonlinear environmental systems.

In this study, ANN is used to model the performance of the PTIET, which is one such complex nonlinear environmental system. While modeling the plant performance based on material and energy balance-based analytical models can be done in theory, such an exercise would be extremely complex to undertake and the model could become unwieldy and cumbersome to apply. Further, to develop an analytical model that can be robust and capture the complex system dynamics would be a very tall order. Thus, for this study an ANN was chosen to model the system, as it is able to capture the interactions between the parameters and the input and output, albeit in a black-box manner. Though, one of the criticisms of ANN models is that it does not help obtain a fundamental understanding of the system, for applications such as this study that is not even necessary. However, a model that can predict as accurately as possible the treated wastewater quality is a very useful tool toward managing the proper functioning of the treatment plant.

The multilayer perceptron artificial neural network (MLP-ANN) model was chosen for formulating the ANN model. The Levenberg–Marquardt feed forward back-propagation algorithm was used to develop the model. An MLP-ANN topology, in general, comprises of three distinct layers namely input layer, an output layer, and any number of hidden layers between the input and output layers. At the input layer, data are introduced into the ANN model. The hidden layer which consists of extremely large number of neurons is the processing section of the model. It is here that the computation of the weighted sum of the input signals and combination with a bias is carried out. This forms the pre-activation signal for the hidden layer which is then transformed by the hidden layer activation function to form feed forward activation signals that leaves the hidden layer. Activation functions are used to transform the activation level of neuron, which is the weighted sum of inputs, into a linear output signal. At the output layer, in a similar fashion, the hidden layer activation signals are modified by weights, biases, and output layer activation function to form the network output. This output is compared with the desired target, and the error between the two is calculated. This error associated with the output is propagated back through the model, and the network parameters such as weights and biases are adjusted accordingly. Such a back propagation computation technique is continued for several iterations till a minimization of error occurs.

3.1. Steps in the development of the ANN model

The ANN model development for the CETP under study was done systematically via the following steps:

Step 1: Data collection, identification, and preprocessing of model input and target data
Step 2: Design and construction of the ANN model using the MATLAB R2016b software
Step 3: Training the model with a part of the input and output data
Step 4: Assessing the performance of the trained ANN model in terms of various statistical parameters
Step 5: Validating the model with the remaining data not used for training
Step 6: Assessing the performance of the model with the validation in terms of various statistical parameters

3.2. Data processing

The wastewater quality data, on careful investigation yielded 240 viable wastewater quality data which could be used in the ANN training and validation process. The sets of raw wastewater quality data, henceforth referred to as the input data, and treated wastewater quality data, henceforth referred to as the output data, consisted of the following water quality parameters: COD, TDS, TSS, chlorides, TA, and TH. The schematic of the ANN model for predicting the CETP performance is given in Fig. 3.

The input and target data sets were preprocessed to remove constant values and subjected to the *mapminmax* preprocessing function of MATLAB. The CETP performance data set was carefully investigated and the following conclusion was arrived at. It was decided to use only six data sets namely cod_{in}–cod_{out}, tds_{in}–tds_{out}, tss_{in}–tss_{out}, $chlorides_{in}$–$chlorides_{out}$, ta_{in}–ta_{out}, th_{in}–th_{out} for the purpose of modeling because sufficient bod_{in}–bod_{out} data sets were not available. Also the parameters $sulfide_{out}$–pH_{out} did not vary significantly over the entire period of data collection and hence were omitted. Thus, the input–output data were grouped into 12 vectors—6 input vectors (cod_{in}, tds_{in}, tss_{in}, $chlorides_{in}$, ta_{in}, th_{in}) and 6 output vectors (cod_{out}, tds_{out}, tss_{out}, $chlorides_{out}$, ta_{out}, th_{out}). Before initializing network training the data vectors were preprocessed to remove constant rows and scaled.

3.3. ANN model architecture, training and validation

A multilayer perceptron feed forward neural network model with back propagation learning was constructed to predict the performance of the CETP in terms of six wastewater quality parameters. A single hidden layer with 200 neurons was used (Fig. 4). The hidden layer and output layer signals were activated using transfer functions such as *tansig* and *purelin*, respectively. The mean square error was chosen as performance goal function. Performance goal and minimum performance gradient was and set to 0.001and 10^{-14}, respectively. By trial and error, the value of learning rate was varied between 0.1 and 1.0 and was set at 0.2. A maximum of 1,000 epochs was used to converge the computation. As mentioned earlier, training stops when any of these conditions are met. The values of other training parameters were maintained at default levels.

The training of the network, and the network performance was tested with a set of 200 data sets. The remaining 40 of the 240 data sets were then used for validating the trained model.

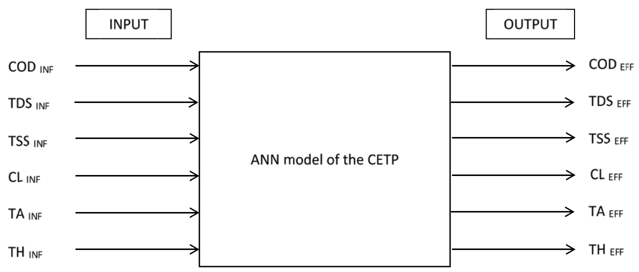

Fig. 3. Input and output variables of the ANN model of the CETP performance.

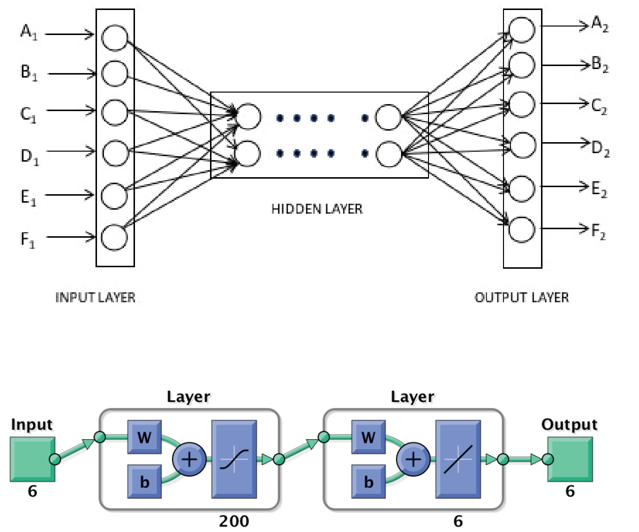

Fig. 4. (a) Architecture of the back propagation ANN network and (b) Neural network diagram.

4. Results and discussion

The robustness of the ANN model developed using 200 input–output data sets was evaluated from the normalized root mean square error (NRMSE) and averaged relative error (ARE) between the observed value and the value predicted by the ANN model. The modeling test results were further analyzed by generating the plots of correlation coefficient (R) and error histogram which serves as an additional criterion for selection of optimal network structure. Table 2 presents the performance of the network during the training and validation of the model in terms of the R of all the water quality parameter model outputs vs. observed values. The training model gave an R of 0.9986 (Fig. 5) and during the validation phase the model gave an R of 0.9735, which indicates a robust performance. For each of the individual water quality parameters of COD, TDS, TSS, chlorides, TA, and TH, the ARE during the training of the model was found to be less than 10% for all parameters except TSS, for which it was found to be 18% (Table 3). For the 40 data sets used for validating the model, ARE was found to be below 31% for all the parameters except for TSS, for which it was 75% (Table 3). The NRMSE is less than 0.2 for the model training results and less than 1 for all the parameters in the validation step.

The performance of the model in predicting output data of the 40 data sets used for validation purpose for each of the water quality parameters can also be seen in Fig. 6. The model has predicted the output values with a great deal of accuracy for TDS, as can be seen from the manner in which the model output values (referred to as "Predicted by the ANN model" in the figure) overlay the actual, observed values (referred to as "Measured" in the figure). The next best prediction is seen for TH and chlorides. The model seems to underpredict the TA for some data points. There appears to be consistent overprediction of TSS, which is reflected in the highest ARE for TSS in Table 3.

To further analyze the performance of the model, the trained model was fed with the minimum, maximum, and mean values of the input data set to see how closely it predicts the corresponding output values. Table 4 presents the results of this study. It is seen that the relative error of the output predicted by the model vs. the observed value is less than 20% for all except 4 of the 18 values tested.

5. Summary and conclusions

The study presents the performance of the CETP located at Pallavaram for treating tannery wastewater from the second largest tannery cluster in Tamil Nadu. The quality of the raw and treated wastewater of the CETP has been obtained for a 1-year period and covers the water quality parameters of pH, COD, BOD, TSS, TDS, TA, TH, chlorides, sulfides, sulfates, total chromium, and oil and grease. As the plant does not receive raw chrome tanning effluent, the chromium levels in the influent wastewater is zero. The sulfides are completely removed in the equalization basin. The oil and grease is removed by the units in the tannery cluster before discharging to the CETP, hence the raw wastewater to the CETP does not contain any oil and grease. Thus, the water quality parameters of pH, COD, TSS, TDS, TA, TH, and chlorides were picked for further study. It was found that the plant is unable to meet the Central Pollution Control Board discharge standards for tannery CETPs for COD, TDS, chlorides, and sulfides most of the time in the 1-year period under study. The standards for TSS are not being met consistently.

The performance of the plant has been modeled using ANNs in order to facilitate prediction of the treated wastewater quality given the raw wastewater quality. A Levenberg–Marquardt feed forward back-propagation neural network with two hidden layers and 200 hidden neurons was used to develop the model. The model was trained on 200 data sets and validated for another 40. The model performance was evaluated based on several statistical parameters and found to be performing exceedingly well. Thus, it has been demonstrated that the ANN model can be used for predicting the performance of the Pallavaram CETP.

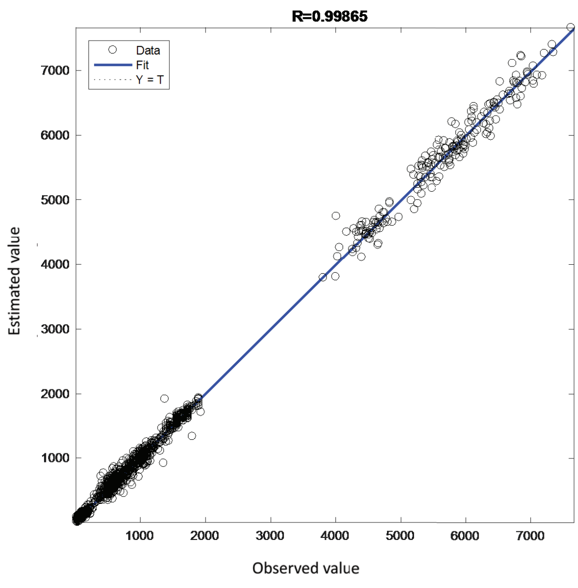

Fig. 5. Parity plot of the value estimated by the model vs. the observed value after the training of the ANN.

Table 2
Summary of the performance of the ANN model in the training and validation phase

Phase	Number of data sets used	Correlation coefficient (R) of model predictions with observed values	Performance in terms of overall mean square error for prediction of all the six water quality parameters
Training	200	0.9986	18,210
Validation	40	0.9735	96,872

ANN, artificial neural network.

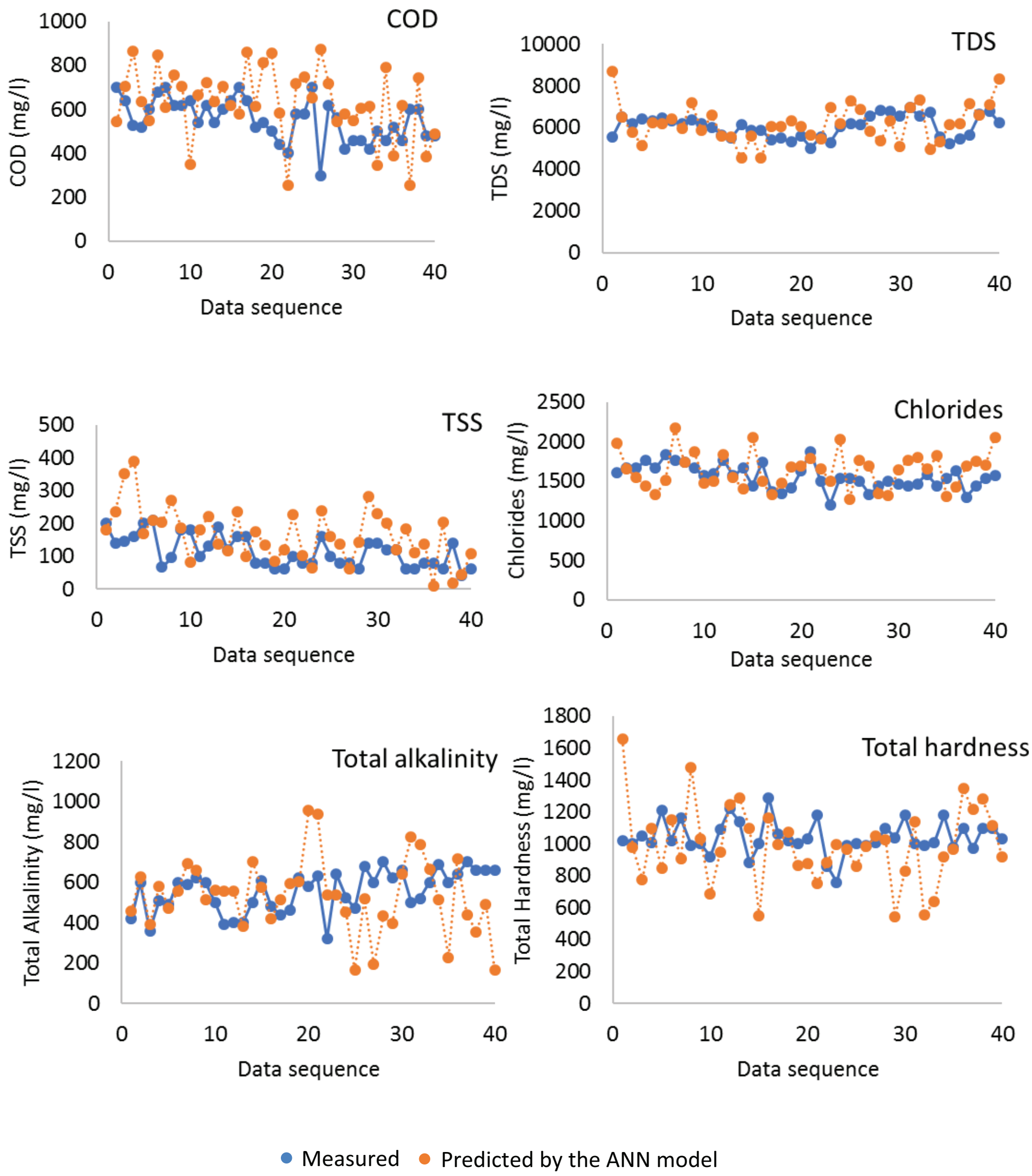

Fig. 6. Validation of the ANN model—comparison of the observed water quality parameter with that predicted by the ANN model.

Table 3
Statistical parameters for prediction of treated water quality in the training and validation phase

Treated water quality parameter	Training data set (200 sets)		Validation data set (40 sets)	
	Averaged relative error (%)	Normalized root mean square error	Averaged relative error (%)	Normalized root mean square error
COD	9.97	0.155	31.34	0.347
TDS	3.36	0.040	12.62	0.168
TSS	18.09	0.206	75.80	0.818
Chlorides	2.53	0.029	15.30	0.177
Total alkalinity	6.56	0.061	28.59	0.364
Total hardness	4.14	0.049	18.99	0.243

COD, chemical oxygen demand; TDS, total dissolved solids; TSS, total suspended solids.

Table 4
Validation of the model using the minimum, maximum, and average values of the raw wastewater quality and comparing the output model with the corresponding observed value

Water quality parameter	Inputs given to the model	Output predicted by the model	Observed value pertaining to the given input	Relative error (%)
Minimum observed values of the raw water quality				
COD	4,000	623	540	15.33
TDS	3,650	3,511	3,810	7.856
TSS	740	134.17	80	67.72
Chloride	900	963	1,400	31.19
TA	60	241.58	380	36.43
TH	480	1015	920	10.33
Maximum observed values of the raw water quality				
COD	10,400	607	440	38.14
TDS	10,716	8,524	6,800	13.01
TSS	5,260	428.9	390	9.98
Chloride	2,666	1,128.5	1,733	34.88
TA	1,080	764	710	7.71
TH	1,580	895.8	1,180	21.05
Mean observed values of the raw water quality				
COD	6,504.7	869.5	700	24.12
TDS	5,525.6	4,911.7	5,590	12.13
TSS	2,054.5	229.3	110	33.3
Chloride	1,641.8	1,620	1,666	2.71
TA	504.5	543	600	9.38
TH	1,187.7	1,009	1,060	4.86

COD, chemical oxygen demand; TDS, total dissolved solids; TSS, total suspended solids; TA, total alkalinity; TH, total hardness.

List of abbreviations

CETP — Common effluent treatment plant
ANN — Artificial neural networks
COD — Chemical oxygen demand
TDS — Total dissolved solids
TSS — Total suspended solids
Cl — Chlorides
TA — Total alkalinity
TH — Total hardness
TNPCB — Tamil Nadu pollution control board
PTIETC — Pallavaram Tanners Industrial Effluent Treatment Co.
BOD — Biochemical oxygen demand
MLP-ANN — Multilayer perceptron artificial neural network

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