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Experimental investigation and artificial neural networks ANNs modeling of electrically-enhanced membrane bioreactor for wastewater treatment

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ABSTRACT

In this work, a new configuration of an electrically-enhanced membrane bioreactor has been introduced to treat medium strength wastewater at Masdar City, Abu Dhabi, United Arab Emirates (UAE). The integrated setup enhanced the reduction of wastewater contaminant concentrations. The investigated components in this study were chemical oxygen demand (COD), orthophosphates (PO_4^{3-}-P) and ammonium (NH_4^+-N). The percentages of COD, PO_4^{3-}-P, and NH_4^+-N removal obtained were 98, 99, and 98%, respectively. Variation in environmental compositions such as mixed liquor dissolved oxygen (DO), volatile suspended solids (MLVSS), pH, and electrical conductivity influenced the effluent concentration of wastewater components. Artificial neural networks (ANNs) based ensemble model was used to model the experimental findings of COD, PO_4^{3-}-P and NH_4^+-N removal given the initial mixed liquor compositions. Comparison between the model results and experimental data set gave high correlation coefficients for COD (r = 0.9942), PO_4^{3-}-P (r = 0.9998) and NH_4^+-N (r = 0.9955).

1. Introduction

Electrokinetic treatment has been a commonly applied water purification technique since the 20th century [1]. Contaminated water is subjected to an electric field between a cathode and anode arrangement [2]. The electrical field releases charged particles, particularly highly charged hydroxide ion species, into the contaminated water which facilitates the agglomeration of contaminated particles and impurities [3,4]. Once agglomerated, the particles precipitate and can subsequently be removed from wastewater. This method of treatment is ideal for purifying water containing contaminants such as metals, colloids, and soluble inorganic and organic pollutants [5].

On the other hand, membrane bioreactor (MBR) technology combines activated sludge process characterised by a suspended growth of biomass with membrane filtration [6,7]. The membrane in the membrane bioreactor (MBR) can be submerged inside the reactor or used externally in side- stream applications [8,9]. The submerged MBR, in particular, offers the advantages of low energy consumption, low pumping costs, and small environmental footprint [10–12]. A hybrid wastewater treatment technique whereby MBR and electrokinetic treatment can be carried out concurrently further reduces the environmental footprint of wastewater treatment and improves effluent quality. A recently developed submerged membrane electro-bioreactor (SMEBR) has proven its capability to produce better water quality effluents [13–15]. Ibeid et al. reported that coupling electrokinetic treatment with MBR can enhance the removal of soluble microbial products and colloidal organic materials, change of the morphology of the suspended solids, and reduction of MBR process constraints [14]. Hasan et al. investigated the potency of the hybrid technology for wastewater treatment employing electrical field and microfiltration in a nutrient-removing activated sludge process. Removal efficiencies of 99, 99, and 92% for ammonium (NH_4^+-N), orthophosphates (PO_4^{3-}-P), and chemical oxygen demand (COD), respectively, were recorded [15]. Results from previous attempts to integrate electrokinetic treatment with MBR technology for wastewater purification are summarized in Table 1. To the best of our knowledge, the previous configurations were not adapted to treat municipal wastewater with high nutrient composition in an arid region such as the Middle East. The temporal fates of each of the major components removed through this integrated tech-

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Table 1
Removal efficiencies from the integration of electrokinetic treatment with MBR.

Source of influent	% removal			Reference
	COD	PO_4^{3-}-P	NH_4^+-N	
Screened raw municipal wastewater	–	>98	–	[16]
Synthetic wastewater	94.3	86.6	100	[17]
Synthetic domestic wastewater	90	–	95	[18]
Synthetic wastewater	96	98	70	[19]
Screened raw municipal wastewater	95	99	–	[20]
Synthetic wastewater	96	98	–	[21]
Domestic sewage	>95	>90	>99	[22]
Screened de-gritted raw municipal wastewater	92	99	99	[10,15]

nology have also not been modeled for prediction purposes. In this research, a new (intensified) configuration of electrically-enhanced MBR has been introduced to treat medium-strength municipal wastewater at Masdar City, Abu Dhabi, United Arab Emirates (UAE). Unlike other studies with a pair of electrodes, this new configuration involves two pairs of electrodes for improved treatment performance.

The removal of wastewater contaminants from processes involving electrokinetics and MBR is generally complicated and dependent on many factors, for example, initial influent concentration of contaminants [23], applied current density and electrical potential [24], types of electrodes [25], and biological and chemical interactions between contaminants [26]. This calls for a non-linear modeling technique such as artificial neural networks (ANN) that can account for the complexity and interdependence of the process. Therefore, understanding the dynamics of integrated electrokinetic and MBR treatment approach through artificial neural networks (ANN) modeling approach is necessary.

Some studies have used artificial neural networks (ANN) modeling to predict some wastewater effluent components. Aber et al. used ANN to develop a model for the prediction of effluent Cr(VI) concentration using electrokinetic treatment process from synthetic and real wastewater at certain operating conditions [27]. A 3-layer feed forward backpropagation network gave high correlation coefficient ($R^2 = 0.976$) with the experimental data, which shows that the model is able to accurately predict the concentration of residual Cr(VI) in the effluent. Similarly, Daneshvar et al. developed an ANN model for predicting the performance of electrokinetic process at decolorizing textile dye solution and the model was found to be effective at predicting residual textile dye concentrations [28]. Also, a feed-forward neural network trained by batch backpropagation algorithm has been employed to model the effluent chemical oxygen demand (COD), total organic carbon (TOC), and oil and grease concentrations of a membrane sequencing bioreactor treating hypersaline oily wastewater [29]. In process scale-up and for large-scale purposes, ANN modeling has been applied for predicting the reduction of effluent biochemical oxygen demand (BOD) and suspended solids (SS) in a plant which treats 1 million m^3/d of wastewater in the Greater Cairo district of Egypt [30]. ANN modeling has also been used for the prediction of the dynamics of BOD, COD, SS, and total nitrogen (TN) removal in a full-scale wastewater treatment plant (WWTP)—Cheonan WWTP—in Korea with a total design capacity of 150,000 m^3/d [31] and estimation of the treatment performance of the Doha West WWTP in terms of the removal of BOD, COD, and total suspended solids (TSS) [32].

In all previous modeling techniques, three remarkable differences are: the type of wastewater, the wastewater treatment technique, and the contaminants removed. In the current study, we focused on achieving high removal rates using a newly configured electrically-enhanced MBR for three main wastewater components: soluble COD, NH_4^+-N, and (PO_4^{3-}-P). We also aimed at using ANN for deriving a model that can predict effluent concentration given initial feed compositions. Experimental data were obtained for influent and effluent pollutant concentrations. The data was trained using given inputs and effluent concentrations as the outputs. Finally, the performance of the model was evaluated by comparing the predicted against experimental findings.

2. Materials and methods

2.1. Experimental setup and materials

Municipal wastewater obtained from Masdar City, Abu Dhabi (UAE) was collected and purposefully not pretreated or prescreened in order to test the efficiency of the treatment system without primary clarification, thereby further reducing environmental footprint. This new configuration comprised of two vertical (rectangular) anodes, two vertical cathodes, and a microfiltration membrane with 0.4 μm pores. The anodes were made from porous aluminum sheets with 40% porosity while cathodes were thin stainless steel perforated sheets (Fig. 1).

The treatment reactor was a rectangular vessel made of polycarbonate sheets. Activated sludge consisting of microbes, obtained from the membrane bioreactor (MBR) plant at Masdar City, was fed to the treatment reactor. The raw wastewater with varying influent concentration of pollutants from Masdar City was then continuously fed into the reactor at a food-to-microorganism (F/M) ratio of 0.59 1/d in order to ensure microbial decomposition of COD and growth of microbes. Stirring was ensured at the filtration zone by keeping the dissolved oxygen (DO) between 5 and 8 mg/L so as to activate the microbial content of the sludge and reduce deposition of reactor content on the membrane. DO was measured using HQ 40d multi meter.

The activated sludge also ensured the conversion of NH_4^+-N to nitrates (NO_3^--N) via nitrification and subsequent conversion of NO_3^--N to nitrogen gas (N_2) (i.e. denitrification). Denitrification (or anoxic activity) was maintained between each anode and reactor wall by keeping the dissolved oxygen concentration (DO) at 1–2 mg/L. Air concentrations were controlled by adjusting the air flow rates obtained from the Cole Parmer 150 mm correlated EW-03217-30 air flow meters connected to the diffusers. No air bubble diffusers were fixed in the anoxic zone and the air concentration in the anoxic zone was monitored to be between 1 and 2 mg/L. For this study, the membrane retained the microbes in the reactor to enhance biological treatment, prevent wash-out of microbes, and promote further purification of the reactor content through filtration. The electric field between the electrodes stimulated the electromigration of pollutants between the electrodes. Thus, pollutants' removal by the electrodes was ensured by electrochemical reactions leading to precipitation inside the reactor and deposition of pollutants on the electrodes, in accordance with their charges [3]. In particular, electrocoagulation has been known to be a very effective method for PO_4^{3-}-P removal since biological activity does not adequately remove PO_4^{3-}-P [13,15].