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Theoretical investigation of the influence of operating conditions on the treatment performance of an electrically-induced membrane bioreactor

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ABSTRACT

This study aimed at investigating the impact of operating conditions on the treatment performance of an alternative method of wastewater treatment. The investigations were carried out in a hybrid reactor which combined simultaneous biodegradation of organic pollutants through microorganisms, membrane filtration through a submerged microfiltration (MF) membrane, and electrocoagulation process via application of electric field intermittently supplied. The theoretical investigations included mathematical modelling to determine the impact of the variations of process parameters such as current density (CD), hydraulic retention time (HRT), sludge retention time (SRT) and pore diameter of anode (dp) on the mixed liquor volatile suspended solids (MLVSS), and the removal of chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), iron (Fe), nickel (Ni), and chromium (Cr) from raw municipal wastewater directly supplied from the main sewer (without pre or primary treatment) at Masdar City, Abu Dhabi, United Arab Emirates. CD was varied between 5 and 20 A/m^2 with a step size of 10 A/m^2; HRT was varied by changing the influent flow rate between 20 and 50 L/d with a step size of 10 L/d; SRT was changed from 5 to 20 d using a step size of 5 d; and dp was changed from 0.2 to 0.5 cm. It was observed from the theoretical results obtained that the removal of COD, TN, and TP from the wastewater was favored in the hybrid unit by increasing the CD or HRT and decreasing the porosity of anode.

1. Introduction

The tendency of membrane bioreactors (MBRs), to experience process constraints including rapid fouling during operation is dependent on many factors [1–4]. These factors include operating parameters, sludge characteristics, membrane characteristics, and feed water characteristics. Operating conditions such as hydraulic retention time (HRT), sludge retention time (SRT), and aeration intensity determines the propensity of operational restrictions in wastewater treatment using membranes. A decrease in HRT for the same reactor volume would lead to an increase in volumetric loading and transmembrane pressure (TMP). This decrease in HRT will increase the mixed liquor suspended solids (MLSS) in the bioreactor and reduce the filtration rate of reactor content [5–9]. On the other hand, Ueda et al. [10] found out that MLSS concentration would reduce when SRT is decreased for the same reactor volume, thereby, leading to reduction in sludge viscosity and improvement in membrane filtration over time. The composition of influent wastewater also influences fouling in the MBR [11]. Gao et al. [11] concluded that a full characterization of the feed might be a viable tool for membrane performance predictions. Zhang et al. [12] also investigated the impact of organic loading on membrane filtration in submerged MBR and observed less adverse effect on membrane flux at steady state conditions when fluctuating loading of influent was ensured.

In this paper, the modelling of the effects of operating conditions on the removal of contaminants from raw municipal wastewater in a MBR integrated with electrokinetic phenomenon is discussed. The integration of electrokinetics with a MBR can be ensured by the insertion of electrodes in the MBR. The release of electrocoagulants from an anode would enhance the coagulation and precipitation of polluting ions, and breaking down of colloids [13]. The mechanisms involved during aluminum electrocoagulation, as provided by Chaturvedi [14], are as follows:

$$\text{Anode}: Al(s) \rightarrow Al^{3+}(aq) + 3e^{-} \quad (1)$$

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Nomenclature

cm	Centimeter
d	Day
g	Gram
h	Hour
L	Liter
mm	Millimeter
min	Minute
s	Second
V	Volt

Symbols

S_I	Inert or un-biodegradable soluble organic material
S_A	Acetate
S_S	Readily biodegradable organic substrates
CODs	Soluble COD
S_{NO_3}	Nitrate plus nitrite nitrogen
S_{NO_4}	Ammonium plus ammonia nitrogen
S_{N_2}	Nitrogen gas
S_{PO_4}	Inorganic soluble phosphorus, primarily ortho-phosphate
X_{AUT}	Nitrifying organisms that participate in nitrification
X_{AlOH}	Aluminum hydroxide composition as $Al(OH)_3$
X_{AlP}	Precipitate of aluminum hydroxides formed as aluminum phosphates
X_H	Heterotrophic organisms
X_I	Inert particulate organic substrates
X_{PAO}	phosphorus accumulating organisms (PAOs)
X_{PHA}	Polyhydroxyalkanoates (PHA)
X_{PP}	Polyphosphates
X_S	Slowly biodegradable substrate
X_{ps}	Particulate substrates
$\xi_{k,j}$	Stoichiometric coefficient of component *j* in process *k*
t	Operation time

$$\text{Cathode}: 3H_2O(l) + 3e^- \rightarrow \frac{3}{2}H_2(g) + 3H^+(aq) \quad (2)$$

Spontaneous production of hydroxides and polyhydroxides such as $Al_2(OH)^{2+}$, $Al_2(OH)_2{}^{4+}$, $Al(OH)^{4-}$, $Al_6(OH)_{15}{}^{3+}$, $Al_7(OH)_{17}{}^{4+}$, $Al_8(OH)_{20}{}^{4+}$, $Al_{13}O_4(OH)_{24,}{}^{7+}$ and $Al_{13}(OH)_{34}{}^{5+}$ would take place after the dissolution of the $Al^{3+}{}_{(aq)}$ ions [15]. Mollah et al. [16] added that, at suitable pH values, Al^{3+} ions are first transformed to $Al(OH)_3$ and finally polymerized to $Al_n(OH)_{3n}$. These transformations are shown in Eqs. (3) and (4).

$$Al^{3+}(aq) + 3H_2O \rightarrow Al(OH)_3 + 3H^+(aq) \quad (3)$$

$$nAl(OH)_3 \rightarrow Al_n(OH)_{3n} \quad (4)$$

Once the highly charged metal cations are released into the solution, they destabilize colloidal particles by forming complexes of polyvalent oxyhydroxides [17]. These compounds formed by the anodic ions have high adsorption properties which enhance the formation of aggregates with pollutants.

In addition to the MBR operating parameters, certain operating conditions also affect the performance of electrokinetic treatment in an electrically-enhanced MBR. These operating conditions include current density (CD), wastewater conductivity, anode material, pH and exposure time to electric field. CD determines how much anodic ions are released into the solution. Excessive CD is not favorable since it increases the chance of wasting energy in heating up the water and reducing contaminants' removal efficiency [18–20]. The passage of current through the anode also ensures the electrolysis of water; i.e., hydroxide ions (OH^-) are transferred through electrophoretic motion to the anode where anions are oxidized and oxygen bubbles are generated [21–23]. Likewise, hydrogen gas is generated at the negative electrode due to the movement of hydrogen (H^+) ions towards it. Apaydin et al. [24] added that electrolysis also produces hydroxyl radical (•OH) which normally behaves as a strong oxidizing agent and reacts with many organic pollutants forming dehydrogenated orhydroxylated derivatives.

Wastewater conductivity influences the voltage of an electrochemical reactor, power requirements, and treatment efficiency [25]. Also, the anode material determines the rate of the release of cations into the suspension. Aluminum and iron surfaces are known to be effective anode materials but these materials present challenges such as passivation and deposition of foulants [17,26–28]. In addition, the pH of the reactor suspension plays a vital role in the speciation of metal ions, solubility the products formed, and removal efficiency of wastewater contaminants [17]. The distance between electrodes in the reactor and anode pore diameter (dp), which influences the extent of exposure of reactor content to electrocoagulants, is also an important determining factor of process performance [29].

Therefore, the need to investigate the sensitivity of an electrically-enhanced MBR to variations in operating conditions is highly critical to the treatment efficiency of the reactor. The response of the quality of the treated effluent from this reactor to variations in operating factors including CD, HRT, SRT, and dpis presented in this study. The effluent quality is expressed in terms of the concentrations of carbon oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) and metals such as nickel (Ni), chromium (Cr) and iron (Fe). The heavy metals are included because of their adverse and hazardous effects to the environment and human health. The impact of operating conditions on mixed liquor volatile suspended solids (MLVSS) was also investigated.

2. Materials and methods

2.1. Mass balances

The electrically-enhanced MBR can integrate biological removal of wastewater contaminants via activated sludge, filtration through a semi-permeable microfiltration (MF) membrane, and electrocoagulation process aided by current supplied to an aluminum anode. A typical treatment system is represented in Fig. 1.

The general mass balance equation for the removal of components was first obtained by combining the different processes acting in the system as expressed in Eq. (5).

$$V\frac{dS_j}{dt} = Q_{in}S_{j,in} - Q_{out}S_{j,out} - (Q_r + Q_w)S_{j,w} \pm V\sum_{k=1}^{m} r_{b,k} \pm r_{ec,j}V \quad (5)$$

Q and *S* represent the volumetric flow rate and concentrations of components respectively. *V* is the reactor volume, $r_{b,k}$ is the rate of biological transformation of component *j* in process *k*, and $r_{ec,j}$ is the conversion rate of component *j* due to electrocoagulation. The subscripts in, out, *r* and *w* represent the influent, effluent, recirculated sludge and waste sludge, respectively. $\sum_{k=1}^{m} r_{b,k}$ is the sum of all biological processes leading to the biological removal of component *j* in processes *k* = 1 to *m*. The volumetric flow rates can be further expressed by Eqs. (6) and (7).

$$Q_{in} + Q_r = \frac{V}{HRT} \quad (6)$$

$$Q_r + Q_w = \frac{V}{SRT} \quad (7)$$