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Impact of continuous and intermittent supply of electric field on the function and microbial community of wastewater treatment electro-bioreactors

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ABSTRACT

The application of electro-technologies to existing biological treatment methods in the United Arab Emirates (UAE) requires further understanding of how microorganisms respond to said electro-technologies. This is necessary in order to optimize and enhance the treated effluent water's quality. Therefore, the primary objective of this research study was to evaluate the microbial communities present in a bio-electrochemical reactor under different operating conditions where variables such as current density and exposure time to electric field were modified in order to achieve system process stability. This study was divided into three Phases. In Phase 1, a laboratory scale study was conducted at different current densities ranging between 5 and 20 A m^{-2} continuously supplied with no addition of substrate. In Phase 2, a laboratory scale study was conducted at continuous supply of electric field at different current densities ranging between 5 and 20 A m^{-2} (Stage 1), and at intermittent supply of electric field at constant current density of 15 A m^{-2} (Stage 2). In each Phase, biokinetics (bacterial counts, growth rates and doubling times), and substrate utilization rate (organic removal) were assessed. Overall, results showed that continuous and intermittent supply of electric field significantly increased observed bacterial counts, growth rates, and soluble chemical oxygen demand (sCOD) removal at lower current densities. High resolution melting analysis (HRM) from Phase 3 indicated that intermittent supply of electric field caused a shift in the microbial population structure in a wastewater bioreactor, while no shift in microbial community population structure was observed in reactors supplied with constant current densities. Taken together, the results presented here indicate that introducing low intermittent or constant electrical current densities to existing biological treatment methods in the UAE has the potential to lead to more efficient and improved reactors for the treatment of wastewater.

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1. INTRODUCTION

The UAE, which lies in the southeastern part of the Arabian Peninsula, is classified as an arid zone with low rainfalls and high evaporation rates. A rapid population growth rate coupled with massive industrial developments has significantly contributed to the depletion of water resources in the UAE. Due to a lack of major natural sources of water such as lakes and rivers, the UAE mainly depends on three sources of water: groundwater (63.6%), desalinated water (29.2%), and treated wastewater (7.2%) [1]. The unbalanced equation of water conservation has led the UAE government to reconsider collecting, treating and reusing the huge amounts of generated wastewater in order to create a viable source of water for landscaping and agricultural purposes. Therefore, the quality of wastewater treatment plants (WWTPs) effluents is a primary concern as poor quality effluent poses a risk of introducing a significant amount of nutrients (nitrogen and phosphorous), pathogens, and metals into either water receptors or the soil. Several technologies have been widely used in the UAE for wastewater treatment such as conventional activated sludge processes (ASPs) and membrane bioreactors (MBRs). Nevertheless, contemporary wastewater treatment facilities occupy a huge

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amount of real-estate due to the necessity to construct various operational units, as each unit is dedicated to the removal of a distinct wastewater pollutant. A typical WWTP contains equipment to screen incoming sewage from collectors, tanks for primary (physical-chemical) treatment, tanks for secondary (biological) treatment, sedimentation tanks after biological treatment, special facilities for phosphorous removal, facilities for ammonia removal, and disinfection. Furthermore, additional facilities are built to deal with the waste generated by each operational unit. Due to the high volume and complexity of such waste, the costs of managing a basic WWTP might reach 60% of the total operation costs of the entire plant. Moreover, more advanced treatments of wastewater would dramatically increase capital and operational costs. Hence, innovative solutions in wastewater treatment are of a great importance. The Submerged Membrane Electro-Bioreactor "SMEBR" is a recently developed wastewater treatment solo unit that operates based on the interaction between biological processes, membrane filtration, and electrokinetic phenomena [2]. Preliminary testing of the SMEBR novel technology was carried out in North America [3], but it has been never tested in arid and hyper arid climatic conditions such as in the UAE. Research into this novel technology is in its infancy and further investigations are essential in order to shed light on the physico-chemical and biological changes under electric field. Electro-technologies link with the wastewater treatment processes which promise effective solutions due to their high efficiency, lack of dependence on external chemicals and ease of control [3–10]. Research on the effect of electrical fields on microorganisms is ongoing. In general, when an electric field is introduced in a microbial culture, changes in the microbes' physiology, shape, metabolism, and movement can occur [11]. Even low electrical currents (20 mA) can increase the surface hydrophobicity of microbes and flatten the cell's shape, and slightly larger currents (40 mA) can increase the microorganisms' surface extracellular substances and the net negative surface electrostatic charge [12]. Most electric fields are harmful to bacteria, decreasing microbial activity, decreasing microbial growth and even causing the death of bacterial cells [13–16]. These effects are largely due to electrolysis on the electrodes, which generates a variety of chemical oxidants responsible for most of the inactivation and lethality of applied current [12].

Thus, there is a limited range of electric current which may be used with microbial cultures, without adverse effects. The limited range has been expressed in different ways for different research; for instance one study found that DC fields up to 1.14 $V\,cm^{-1}$ have no adverse effect on mixed aerobic cultures, while another study expressed this limit as being a current density of 12.3 $A\,m^{-2}$ [11,17]. It should be noted that the electrical field's effect is also determined by time of exposure. Sometimes an electrical field within the limited range may even increase microbial growth and activity [17]. The limited DC current may actually, through electro-stimulation or bio-stimulation, enhance bacterial metabolism, membrane permeability and cell growth [11]. Taken together, there is a need for more research on the effect of electrical fields on microorganisms specifically within the context of SMEBRs. Consequently, the main objective of this research study was to investigate the impact of continuous and intermittent supply of electric field on the function and microbial community of wastewater treatment electro-bioreactors.

2. EXPERIMENTAL

2.1. Experimental Design

The research methodology in this paper is divided into three Phases. In Phase 1, the impact of electric field, in the absence of wastewater substrate, on the growth kinetics of living microorganisms in a mixed culture was investigated (i.e. electro-stimulation). A range of current density (5–20 $A\,m^{-2}$) was continuously applied in a 12-h experiment. Phase 2 was then designed to evaluate the response of microorganisms under electric field and in the presence of wastewater substrate initially supplied. Two modes of exposure to electric field were tested; 1) continuously, and 2) intermittently as follow:

- In Stage 1 → continuous supply of electric field at different current densities (5–20 $A\,m^{-2}$) in a 24-h experiment
- In Stage 2 → intermittent supply of electric field at constant current density, obtained from Phase 2–Stage 1, in a 28-h experiment

Furthermore, Phase 3 was carried out to investigate the impact of electric field, continuously applied, on the growth rate of *Escherichia Coli (E. Coli)* pure culture. This was to compare the behavioral responses of pure and mixed cultures under electric field. The current density was selected based on the results from Phases 1 and 2.

2.2. Reactor Design

Fresh activated sludge was brought from Masdar City MBR wastewater treatment plant (Abu Dhabi – UAE) and used immediately. The open system used for this study utilized batch bio-electrochemical cells each filled with 900 mL of fresh sludge and connected to DC power supplies (Fig. 1A) and electric timers when necessary (Fig. 1B). Intermittent supply of electric field of (i) 5 min ON: 10 min OFF (thereafter 5:10), (ii) 5 minutes ON: 15 min OFF (thereafter 5:15), (iii) 5 min ON: 20 min OFF (thereafter 5:20), and (iv) 5 min ON: 30 min OFF (thereafter 5:30) was used in Phase 2–Stage 2. The electrodes (used in all experiments) consisted of rectangular sheets of perforated aluminum (anode with 75% opening and effective surface area of 0.0048 m^2), and stainless steel (cathode) spaced 5 cm apart. Aeration was provided via small cylindrical air stone diffusers placed at the bottom, in order to provide the oxygen necessary (>2 $mg\,L^{-1}$) for aerobic microbial growth and sludge mixing. A reference bioreactor (i.e. 0 $A\,m^{-2}$) was used in Phase 1 and Phase 2–Stage 1 and had no electrodes. The reference bioreactor in Phase 2–Stage 2 was noted as 0:1 thereafter.

2.3. Sampling and Bacterial Counts

A 10 mL sample from each reactor at different time interval was collected frequently from the zone between the electrodes and analyzed for soluble chemical oxygen demand (sCOD) and bacterial counts. The bacteria count analysis was done in triplicate and an average value was recorded. Bacteria count was carried out using the plate count agar method [18]. Serial dilutions between 10^{-1} and 10^{-8} were prepared and 0.1 mL was used to determine bacterial counts in the bioreactor water samples taken. The number of bacteria in the water samples were calculated and reported as colony-forming units (CFU) per mL (i.e $CFU\,mL^{-1}$).

2.4. Soluble Chemical Oxygen Demand (sCOD) and Oxygen Uptake Rate (OUR) Measurements

A Hach HQ40d single-input multi-meter probe was used to monitor dissolved oxygen (DO), pH, temperature (T) and electrical conductivity. sCOD was analyzed in duplicate using Hach COD vials (LCK 314 and LCK 514) and average values were reported. Oxygen uptake rate (OUR) was measured in Phase 1 after cutting off aeration in all bioreactors. The DO probe (HQ40d single-input multi-meter) was then immersed in the sludge through which the

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