Technical and Economic Feasibility of Generating Renewable Energy from Wastewater Treatment Using Microbial Fuel Cells: The West Bank as Case Study

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Abstract: The technical and economic feasibility of microbial fuel cell use in wastewater treatment for energy and resource recovery was investigated. A double chambered-MFC model (DS-MFC) operated by primary effluent wastewater as substrate was used. Four different COD-MFCs groups were constructed in three duplicates (input COD from 342 to 1733 mg/l). Initial COD value, electrode type, and salt bridge size and its concentration were set and fixed for each MFC group. After 15 days-startup period the MFCs were operated for 30 days. COD was measured for the twelve MFCs every two days and output voltage was measured every 24 hours. Results revealed that the COD of the substrate used in MFC at any time is related proportionally to output voltage from that MFC, and a logarithmic model was found that can be used to predict COD for a wastewater sample by measuring output voltage of MFC operated by that sample. Maximum COD removal percentage achieved in this study was 87.1 % which agrees with published research. A maximum output power achieved was 0.585 W/m3 treated. It was found that COD removal behavior for the first group (typical wastewater composition) was second order while the other three groups with higher concentrations was first order. The payback period of the system under consideration was estimated at 8.3 years (infeasible). If we include the environmental and energy challenge benefits of the system to its economic feasibility, the system feasibility could be considered appropriate.

Keywords: Microbial fuel cells, Wastewater treatment, Energy production, Economic feasibility, MFC Kinetics modeling.

1. INTRODUCTION

With globally increasing population, urbanization, and industrialization, the use of fossil fuels has dramatically increased resulting in depletion of those non-renewable resources. As a result the generation of domestic wastewater increased with composite content and negative impacts on the land and water environment. In addition, wastewater treatment plants (WWTPs) worldwide are a high consumer of electrical energy [1-3] which is considered a crucial issue for municipalities [4]. For example, it was found in Greece that the annual energy cost/house related to wastewater treatment only would be estimated at 14 to 16 Euros. Consequently, the use of alternative and renewable energy sources in wastewater treatment such as MFCs is important for reducing overall costs as well as energy cost. This importance extends to developed as well as developing countries to reduce dependence on fossil fuel use and meet the increasing energy demands [5, 6].

Wastewater treatment and energy production sectors in Palestine are growing and need enormous efforts and budgets to be developed to satisfy technical, technological, economic, and environmental standards and regulations. At present only few wastewater treatment plants exist and some of them are with primary treatment level. Most of Palestine rely on Israel in electrical energy supply. Few cities have partial electric supply from local production stations.

MFCs are important, reliable, and effective devices that directly convert the chemical energy stored in the organic matters into electrical energy using microorganisms, organic matter, and anaerobic conditions [7, 8]. Historically, the concept of electricity production using microorganisms was discovered in 1911 [9, 10]. Then it was proven that batch biological fuel cell could produce more than 35 volts [11, 12]. Clear principles for MFCs were identified in 1976 [13, 14]. Extraction of electrical current from MFCs that were operated using wastewater was conducted in the 1980's using pure cultures and artificial electron mediators [15, 16]. Later in the 1980's, it was discovered that the generated electricity could be significantly increased if electron mediators were added [17].

Typical MFC used in testing microbial activity and optimizing materials consists of two compartments: anodic chamber and cathodic chamber, separated by

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salt bridge or proton exchange membrane (PEM) [18-21]. Substrate (organic-rich matter) is added to the anodic chamber, where conversion of organic matter occurs by anaerobic microorganisms [22, 23]. In addition to energy production and organic matter removal from wastewater, MFCs as anaerobic process simultaneously reduce or have minimal or no net-CO_2 emission contributing to climate change reduction [24]. Electrons and protons are produced from oxidation half-reaction of the substrate, electrons transfer from the anode to the cathode using external electrical load (resistance); where protons transfer to the cathode was done through salt bridge [25, 26].

Currently, the emphasis has shifted from only technical, technological, and environmental-friendly MFCs to economic feasible MFCs as well. There is intense interest in increasing the power density level of MFCs and make its operation economically feasible to bring it to large scale application [27].

Although MFC is coming up as a promising technology to treat wastewater; still several challenges remain which need to overcome to commercialize this technology. A highly important challenge of MFCs is the energy loss within the process. Energy loss can occur in different ways in MFCs: activation loss (maybe for initiating the reactions on both electrodes and extracellular electron transfer to the anode), bacterial metabolism loss (due to bacteria acquiring energy by oxidizing the substrate), mass transfer loss (due to limited flux of the reactants to the electrode), and ohmic losses (due to proton diffusion resistance and charge transfer resistance [28]. Besides energy loss, cathode flooding and deformation as a result of high hydraulic pressure is another challenge during air-cathode MFC scaling up[29]. Also, there are several physicochemical factors governing MFCs performance including: operating conditions in anode chamber, pH, alkalinity, substrate type, substrate concentration, and organic loading rates [30].

It was reported that for economic profitability demonstration of MFCs, classical evaluation criteria for investment decisions such as the Net Present Value **AND THE** Internal Rate of Return was used. Three different scenarios, optimistic, pessimistic and most likely scenarios based on the maximum power density of the MFCs were studied. The results show that MFCs are a more economic attractive option. A sensitivity analysis has revealed that the electrode area parameter is the most influential, reducing the MFC profitability for larger electrode areas, whereas the higher the annual growth rates of the electricity price, the higher the MFC profits. [31].

It was found that the cost of materials used in MFCs such as ion selective membrane or nonspecific separators is an important challenge in achieving MFCs economic feasibility. This material cost evaluation must be made in the context of and related to the performance of MFCs [32]. In addition, the type of MFCs model greatly impact their economic feasibility [33]

Depending on several design and operating parameters and variables, MFCs use and efficiency are different. Accordingly, the power generation densities obtained at the anode was ranging from 29 to 4300 mW m^2 with an average of 580 mW/m^2. These design and operating parameters and variables include:

(1) various types of substrates employed in the MFCs (animal manure, primary and secondary domestic wastewater, sludge, urine, agricultural waste, leachate of solid waste, or mixture of it), and various design models of MFCs (single chambered, double chambered, multiple anode chamber, Air-cathode , ceramic cathode, various types of electrodes, and other variables) [34-56]

(2) type of culture, cells count, and biofilm density used (pure, anaerobic, aerobic, yeast, etc) [57-65],

(3) type of cathodic solution (oxygen, ferricyanide, nitrite, or other) [66-69],

(4) type of electrode material (carbon paper, activated carbon, graphite fiber brush, granular activated carbon, MPL-carbon viel, MPL-carbon cloth, PVDF-AC, carbon felt, graphite felt, graphite wool, graphite granules, etc) [70-77], and

(5) startup temperature (5, 10, 25 ^oC, or other) [78-85],

In the first part of this study optimization of microbial fuel cells operating parameters for better removal of organic matter and higher energy production from wastewater was investigated and resulted in an optimized design of MFCs using copper electrode, 10mm size salt bridge made of potassium chloride, and 1M salt solution concentration filled in the salt bridges [86].

In this study and based on the results obtained in the first part, a double chambered Microbial fuel cells (MFCs) was developed and evaluated using copper electrode, 10mm size salt bridge made of potassium chloride, and 1M salt concentration filled in the salt bridges. The wastewater samples were municipal primary effluent mixed with sludge as a substrate. Kinetic modeling of the relationship between COD of substrate in MFC and calculating the economic feasibility of MFCs was performed.

2. METHODS AND MATERIALS

This research was performed mainly by laboratory work, all laboratory work was done at the Environmental Engineering Laboratory of the Civil Engineering Department at An-Najah National University, Nablus.

2.1. Experimental Setup and Design of Experiments

Twelve MFCs were constructed (four groups with three duplicates). Each group have the same COD-substrate concentration. Double chambered-MFCs were used, with copper electrodes, 10 mm-diameter salt bridges for protons exchange, primary effluent wastewater as substrate and anaerobic sludge as source of anaerobic microorganisms.

2.2. MFCs Configuration and Construction

MFCs were constructed using 1-liter glass jars for both anode and cathode chambers as shown in Figure 1. To prevent substrate and/ aerated water from dropping outside the jars during mixing/shaking, an effective volume of 800 ml was used in the MFCs.

Copper electrodes were used and applied for all MFCs; all used electrodes have the same dimensions 7 cm x 4 cm (14.28 cm^3 substrate/1 cm^2 electrode). All Electrodes were soaked into mixed solution of anaerobic sludge and primary effluent wastewater (20% sludge in terms of volume) at 35 ^oC for 3 days; in order to allow culture to grow and form on the anodes surface.

Salt bridges were used as proton exchange media due to its low cost and availability comparing to PEMs. Because it is chemically and electrically inert material. Pyrex Glass tubing were used as structure of the bridges. U-shaped salt bridges were constructed from straight glass tubes and using Bunsen flame for bending to form U-shaped tubes, its dimensions were 10 cm, 8 cm and 10 cm and mm mm diameter and filled with 1 M concentration KCl salt solution used.

In the anodic chamber, primary effluent wastewater mixed with anaerobic sludge was used as substrate. For the cathodic chamber, Oxygen is the best efficient electron acceptor. In this experiment, the cathodic solution used was aerated water. Distilled water was used, 800 mL distilled water was used in each cathodic chamber. Evaporation of distilled water was noticed due to heater and aeration effect; so cathodic chambers were refilled on daily basis. Aerators such as those used in fish tanks were applied to aerate the cathodic chambers; operating was done for 15 minutes intervals; each operating interval was followed by 15 minutes break in order to prevent exhausting of the fishing aerators. It was assured that the amount of aeration is approximately equal in all cathodes.

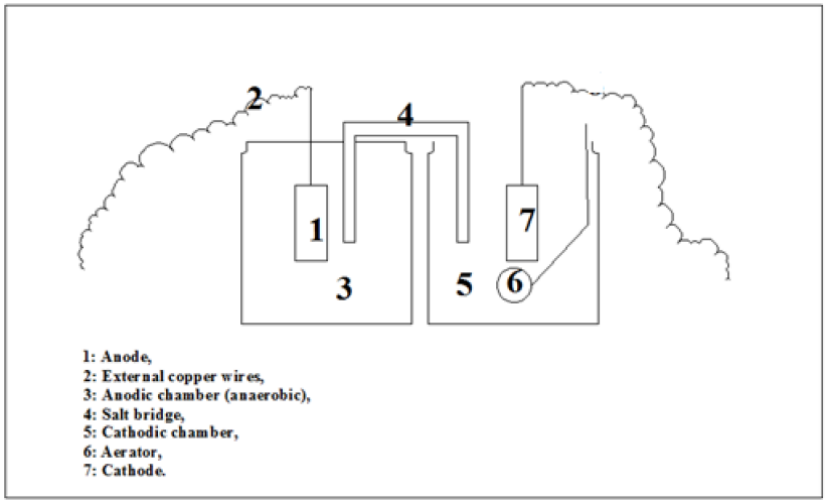

Figure 1: Schematic of DS-MFC used.

2.3. Temperature Control System

In order to keep temperature within 34-36 ^{o}C during operation of the MFCs, temperature control system was constructed and applied at the fume hood were all MFCs were installed. Temperature control system consists of: Arduino, two water proof temperature sensors, two air sensors, heater, Bluetooth device for monitoring and microcontroller.

2.4. Mixing System

One of the obstacles that was faced in this research was mixing of WW and sludge, in order to approximately keep substrates homogeneous in all MFCs. Hot plate stirrer was non-practical solution to solve this dilemma due to two reasons: required number of stirrers was 12 which is impossible to get, the second reason that the mechanism by which hot plate stirrer works is questionable for our application; *i.e*., hot plate stirrer works by applying magnetic field which can affect electrical behavior of the MFCs.

Mechanical system was the main suggestion to solve mixing problem. The first idea was to construct vertical or horizontal mixers that connected to the 12 MFCs with one strong motor; but this idea was rejected because of the existence of salt bridges and electrodes in the anodic chambers.

Finally, shaking plate was proposed and shown to be the best solution. A mechanical shaker was designed and constructed to perform mixing task for the samples, it consists of: geared motor, transition mechanism, bearing, caster wheel and movable box. See Figure **2**.

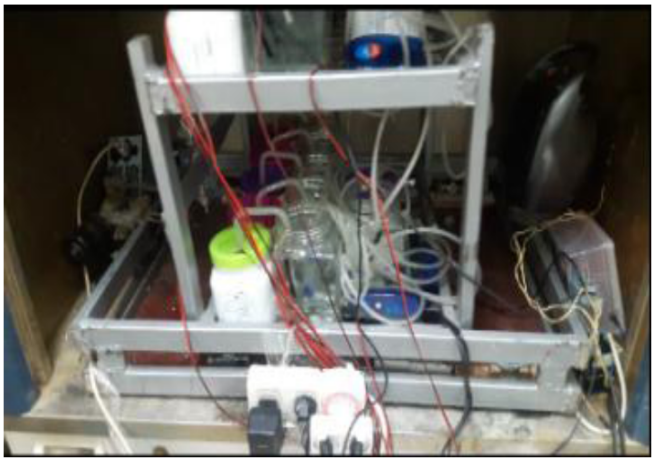

Figure 2: Used mixing system.

2.5. Electrical Panel

An electrical panel was prepared and installed to ease the voltage and power measurements; an electrical panel was prepared. For each MFC, a 1000-ohm resistance was fixed at the electrical panel and connected with the electrodes with copper wires. For all MFCs the length of the copper wires was unified to 1 meter long.

2.6. Wastewater and Sludge Sampling

The wastewater samples were collected from Nablus West wastewater treatment plant (WWTP). WWTP serves a total population of 110,000 capita. Treatment system is conventional Activated Sludge System, with an actual average flow of about 11,000 m^3/day where the design flow is max 15,000 m^3/day**.** WWTP plant contains two main wastewater treatment lines:

- The first one is wastewater treatment line including: grit chamber, primary sedimentation tank, aeration tanks, final sedimentation tanks, filtration and disinfection.
- the second one is sludge treatment line including thickener, anaerobic digester, sludge drying basin, sludge storing, liquor storage tank, gas holder and gas flare [87].

Average influent wastewater characteristics are: COD=990 mg/L, BOD=400 mg/L, TSS=410 g/L, pH=7.8 and conductivity=1500 μs/cm [88].

Samples were collected from the effluent of primary sedimentation tank; in order to get rid of unnecessary solids (See Figure **3**).

Figure 3: Wastewater sampling from primary effluent from Nablus West WWTP.

Primary effluent wastewater was used as substrate for lab-models, the reason for that was to avoid solids in the primary sludge despite that some organics are lost with sludge; *i.e*. COD is expected to be decreased by about 20-30 % through primary sedimentation. Sampling of wastewater from Nablus West WWTP was done in non-rainy days, and after at least 72 hours of any raining fall, to assure that no storm water is mixed with the collected wastewater. Sampling of WW was done from the weirs of the primary sedimentation tank in the WWTP and from various locations along the weir.

WW was collected in a cleaned plastic container with a volume of 10 liters, and then stored at 35 ^{o}C till use after one-two days, in order to assure keeping microorganisms' activity.

Sludge was collected in glass container from the anaerobic digester in the WWTP and stored at 35 ^{o}C until use after one-two days. Table **1** shows the details of the used substrates for each concentration.

COD for the anaerobic sludge and the used wastewater were measured using titrimetric method according to "Standard Methods for the Examination of Water and Wastewater" [89]; they were found to be 48,000 mg/L and 547 mg/L respectively.

Volume of substrate used for each MFC is 800 mL, COD for the mixed sludge-wastewater was directed to be within 300-1700 mg/L; volume of the sludge was calculated using equation 1.

$$\text{COD total} = \frac{(\text{WW VolumeX WW COD}) + (\text{Sludge Volume X Sludge COD})}{Total\ volume} \quad (1)$$

2.7. Operation of Experiment

Twelve MFCs were constructed and fed mainly with wastewater and small quantity of anaerobic sludge. Metabolic behavior is highly affected by the surrounding conditions such as temperature and pH. Anaerobic sludge was used in this study as source of anaerobic microorganisms, it was collected from anaerobic digester in which the temperature is more than 40 ^{o}C and it was there for 12–60 days depending on the temperature.

Since that temperature in the anaerobic digester is near thermophilic conditions (40 ^{o}C – 60 ^{o}C), then it is expected that mesophilic microorganisms (20 ^{o}C – 40 ^{o}C) are very weak in the anaerobic sludge, therefore a startup period is required in order to assure that mesophilic microorganisms were become strong enough [90].

After mixing WW with anaerobic sludge, 15 days startup period was applied at 35 ^{o}C temperature and without connecting salt bridges and electrical circuit in order to allow microorganisms to adapt with the experiment conditions.

After startup of the experiment, COD for each MFC was measured each two-day using titrimetric method. Output voltage was measured on daily basis using Voltcraft M-3860M multimeter.

2.8. Analytical Procedures and Measurements

Two types of measurements were concerned; quality (environmental) measurements and energy measurements. It worth to mention that environmental measurements were performed according to standard methods for examination of water and wastewater [91]. Details of all measurements performed are summarized in the following sections.

2.9. Environmental Measurements

The main environmental/quality measurement in this study is organic matter contents or COD. It was taken one time each 48 hour for all Twelve MFCs.

Sampling from MFCs was performed using pipette; in all sampling times, approximately half of the sample is collected from the first top third of the anodic chamber and the rest from the second top third of the chamber.

Table 1: Details of Substrates used in the MFCs

Group Number	WW Volume (mL)	Distilled Water Volume (mL)	Sludge Volume (mL)	Expected Mixture COD (mg/L)
1	500	300	0	342
2	795	0	5	844
3	785	0	15	1437
4	780	0	20	1733

Generally, Samples were mixed with: standard potassium dichromate digestion solution, sulfuric acid reagent and sulfamic acid in quantities as given in the standard methods. After heating of mixture for 2 hours at 150 ^{o}C and cooling, the mixture was titrated against standard ferrous ammonium sulfate (F.A.S) and using ferroin as indicator. COD was measured for all MFCs substrates day after day, at each time a blank sample was prepared from distilled water and the same reagents used for the samples.

COD was calculated according to equation 2:

$$\mathbf{COD\ (mg\ O_2/l)} = \frac{(A-B)\ X\ M\ X\ 8000}{mL\ sample} \quad (2)$$

Where:

A: mL of F.A.S used for blank,

B: mL of F.A.S used for the sample,

M: molarity of F.A.S (0.05 M) and

8000: milliequivalent weight of oxygen.

COD measurement -COD of anaerobic sludge used: Since that the expected COD of the sludge is too large; it is required to dilute sludge samples using distilled water. 10 mL of anaerobic sludge were taken from the well mixed sample and diluted with 990 mL distilled water. The resulted dilution factor is:

P_1= initial volume of sample/ final volume = 10/ (990+10) = 0.01

The resulted 1 L sample was well mixed using magnetic stirrer. Three COD samples, each 1 mL, were taken. The samples were taken from top, middle and bottom of the beaker containing sample.

Sample volume taken from diluted sludge were 1 mL for each, so the total dilution factor is:

$P=P_1 \times P_2= .01 \times (1/2.5) = 0.004$

Summary of sludge COD measurement are represented in Table **2**.

COD of the primary effluent was expected to be around 500-700 mg/L. Dilution was performed to assure that the measured COD is within allowed range (40-400 mg/L). Summary of initial wastewater COD measurement is presented in Table **3**.

2.10. Voltage and Power Measurement

Voltcraft M-3860M Multimeter was used to measure output voltage (See Figure **4**).

2.11. Kinetic Models for COD Decay in the MFCs

The commonly used kinetic models for environmental applications are 0, 1st, 2nd and 3rd order kinetic equations (see Table **4**).

Table 2: Summary of Sludge COD Measurement

Sample	A (mL)	B (mL)	A-B (mL)	Dilution factor	COD (mg/L)
1	2.9	1.6	1.3	0.004	52,000
2	2.9	1.8	1.1	0.004	44,000
3	2.9	1.7	1.2	0.004	48,000
Blank	2.9				
Average COD for the three samples (mg/L)					48,000

Table 3: Summary of Initial Wastewater COD Measurement

Sample	A (mL)	B (mL)	A-B (mL)	Dilution factor	COD (mg/L)
1	2.7	1.1	1.6	0.4	640
2	2.7	1.4	1.3	0.4	520
3	2.7	1.5	1.2	0.4	480
Blank	2.7				
Average COD for the three samples (mg/L)					547

Table 4: Non-Linearized and Linearized Kinetic Models

Reaction Order	Kinetic Equation		Linearized Kinetic Equation	
Zero	$C_A = C_o - Kot$	**(4)**	$(C_o - C_A) = K_o t$	**(8)**
First	$C_A = C_o e^{-K1t}$	**(5)**	$Ln(C_o / C_A) = K_1 t$	**(9)**
Second	$(1/C_A) = (1/C_o) + K_2 t$	**(6)**	$((C_o/C_A)-1)/ C_o = K_2 t$	**(10)**
Third	$(1/C_A)^2 = (1/C_o)^2 + 2K_3 t$	**(7)**	$0.50(C_A^{-2} - C_o^{-2}) = K_3 t$	**(11)**

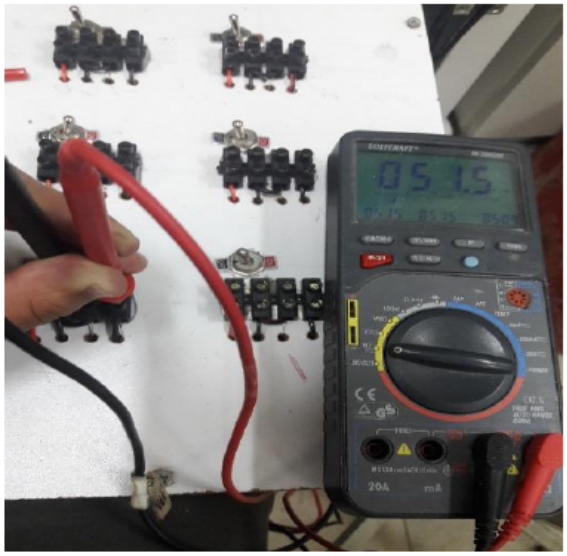

Figure 4: Output voltage measurement.

COD vs time data was used to obtain the most suitable kinetic model for each MFC. The four kinetic equations can be linearized by finding Kt value for each point (COD, time) and plotting t vs Kt for the four kinetic models and determine which the most representative model is.

Linearize kinetic models (equations **4-7**), obtained (see Table **4**).

Regression analysis and kinetic models' data plots were performed using EXCEL.

3. RESULTS AND DISCUSSION

3.1. Wastewater and Sludge COD Measurement Results

The average COD of sludge for three samples was 48,000 mg/l while the average COD for three wastewater samples was 547 mg/l.

3.2. Kinetics of COD Decay

The estimated Kt versus time for the four groups is presented, illustrated, and discussed for the four reaction orders studied (zero, first, second, and third) in the following sections:

a) Group I MFCs

Using the COD measurements obtained versus time for group I MFCs (MFCs 1,2, and 3) with the lowest substrate input among the four groups of 342 mg/l, the correlation factor for the zero, first, second and third reaction order was estimated at 0.8418, 0.8388, 0.9191, 0.6091, for zero, first, second, and third order reaction kinetics respectively. Accordingly, the second reaction order fit the experimental data best (see Figure **5**).

b) Group II MFCs

Using the COD measurements obtained versus time for group II MFCs (MFCs 4,5, and 6) with substrate input of 844 mg/l, the correlation factor for the zero, first, second and third reaction order was estimated at 0.8375, 0.9527, 0.8814, 0.6424, for zero, first, second, and third order reaction kinetics respectively. Accordingly, the first reaction order fits the experimental data best (see Figure **6**).

c) Group III MFCs

Using the COD measurements obtained versus time for group III MFCs (MFCs 7,8, and 9) with substrate input of 1437 mg/l, the correlation factor for the zero, first, second and third reaction order was estimated at 0.9123, 0.9599, 0.9144, 0.6586, for zero, first, second, and third order reaction kinetics respectively. Accordingly, the first reaction order fits the experimental data best (see Figure **7**).

d) Group IVMFCs

Using the COD measurements obtained versus time for group IV MFCs (MFCs 10,11, and 12) with substrate input of 1733 mg/l, the correlation factor for the zero, first, second and third reaction order was estimated at 0.9731, 0.9728, 0.9871, 0.7008, for zero, first, second, and third order reaction kinetics

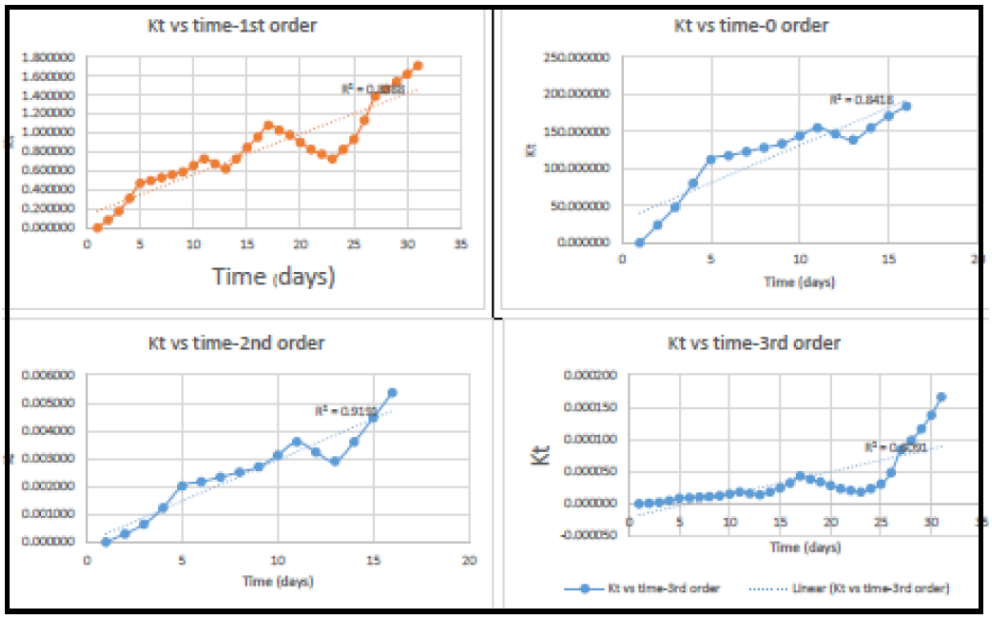

Figure 5: Data and Kinetic Models for the first Group MFCs: MFC 1, 2 and 3.

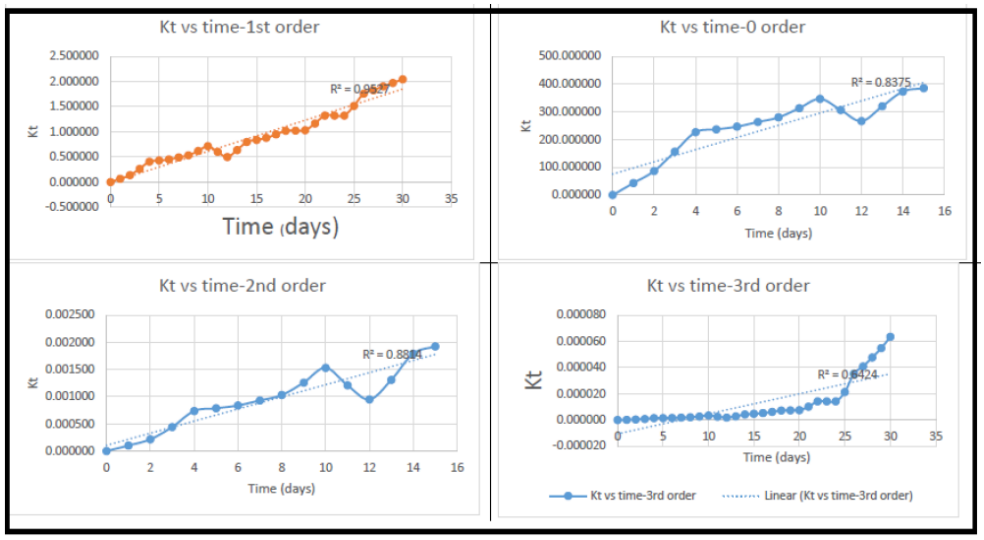

Figure 6: Data and Kinetic Models for the Second Group MFCs: MFC 4, 5, and 6.

respectively. Accordingly, the second reaction order fits the experimental data best (see Figure **8**).

It is noticeable that the correlation factor for the zero, first, and second reaction order for the fourth MFC group are very close an indication of the strength of the relationship between COD measurements and time for the three MFCs. Also, it is an indication of the small portion of the unexplained COD variations or the good-strong data obtained (COD VS Time). The high correlation factors (over 97% for the forth group and about 93% for the third group) explains to what extent the variance of COD measurements explains the variance of the time variable or vice versa.

However, the close magnitude of correlation factors doesn't tell you whether the zero, the first, or the second reaction order or kinetic model is better, or more reliable, or worse than the other two reaction orders. Also, it will not tell you whether the COD data and kinetic model predictions are biased.

In comparing the four MFC groups and corresponding kinetic models it is clear that (i) As the input to MFC substrate COD concentration increase, the kinetic COD decay model change from second order to fist order then to moving between the three: zero, first, and second order, and (ii) The COD Vs Time data and the good linearized fit of the data indicate that

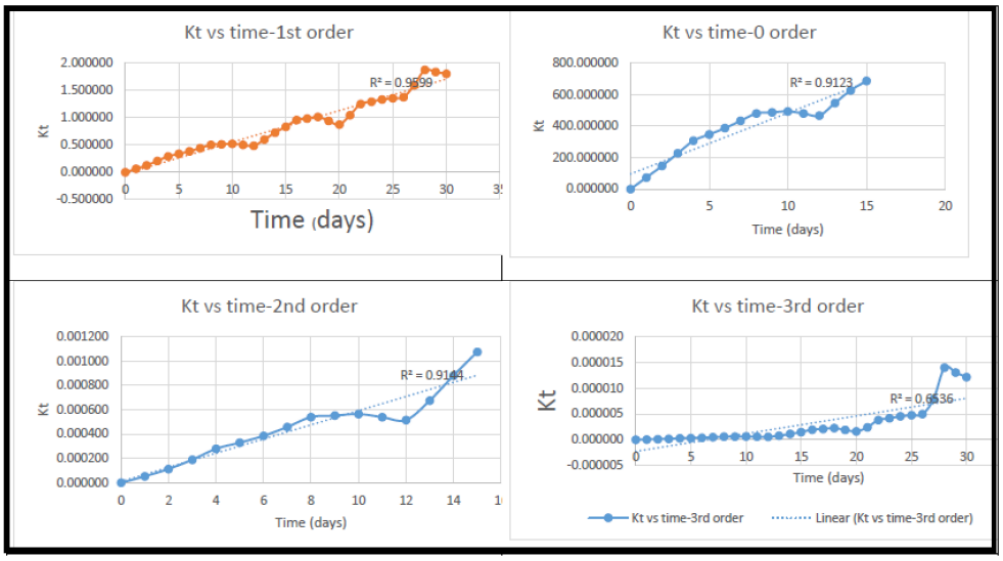

Figure 7: Data and Kinetic Models for the Third Group MFCs: MFC 7, 8, and 9.

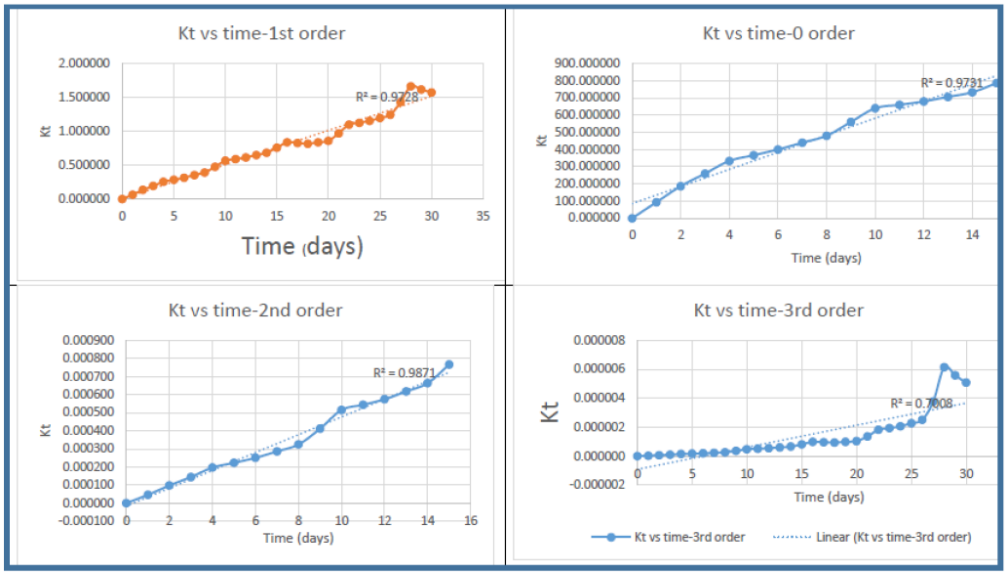

Figure 8: Data and Kinetic Models for the Fourth Group MFCs: MFC 10, 11, and 12.

our data, to good extent, are reasonable. This finding agrees with what was published previously on the impacts of wastewater composition on MFCs performance [92-97].

Knowing that the typical COD concentration out of primary effluent is about the concentration used in the first MFC group, therefore, the second order COD decay kinetic model is the most suitable model to be used to predict COD variation in MFCs with time. In case of higher COD input substrate concentration used such those used in MFCs groups II, III, and IV, first order reaction would be best to describe the behavior of the MFCs (see Figures **9** and **10**). Figure **9** clearly illustrate the best fit of the second order to the measured COD data of the first MFC group while Figure **10** illustrate a reasonable fit of the first order reaction to COD data of the II, III, and IV groups of MFCs.

3.3. Relationship between Output Voltage and Substrate COD

COD data obtained from the four groups (12 MFCs) was plotted versus output voltage to investigate the relationship between the two (see Figure **11**). Figure **11** indicates that COD (which was initially measured VS time) versus the output voltage increases rapidly at first, but then steadily slows down.

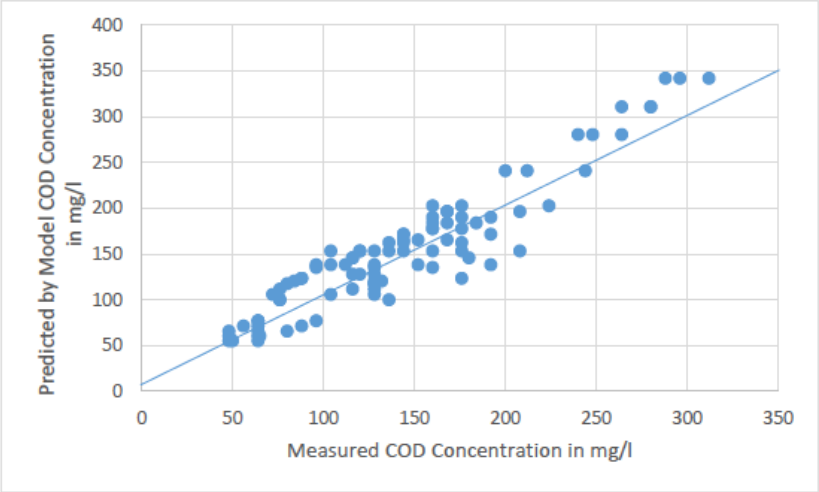

Figure 9: COD predicted by the Second order reaction kinetic for the First Group MFCs.

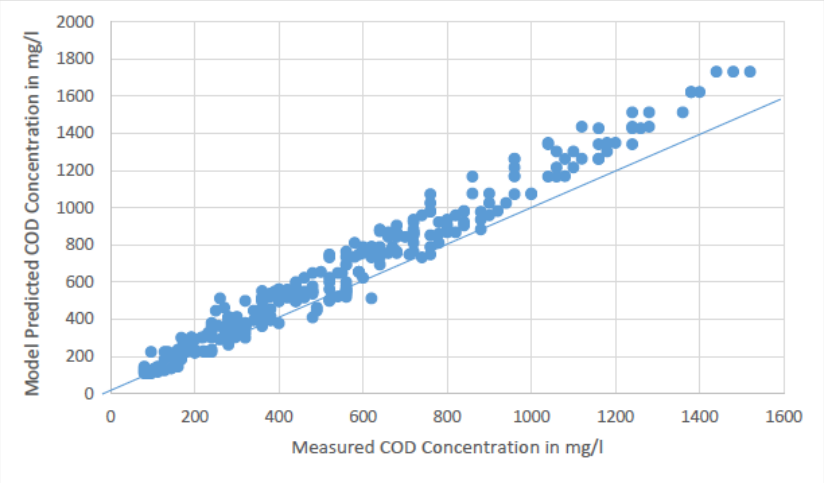

Figure 10: COD predicted by the First order reaction for Group II, III, IV MFCs.

This feature of the data indicates the suitability of the use of natural logarithmic regression model for fitting it (COD as model output, Y and output voltage as model input X). Natural logarithmic regression model was applied on the measured data for the twelve MFCs and the following relationship was obtained (Figure **11**).

COD (mg/L) = 229.85 Ln (V)-1039.6

where V is output voltage (mV).

The rate of COD increase in MFCS is controlled in nature and extent by the slope of the model = 229.85. As the output voltage rapidly increase, the intersect = 1039.6 will have a minor effect on predicted COD.

This model can be simply used to predict COD concentration of any wastewater sample in MFC , by measuring the output voltage of a MFC.

This model can be used to indicate COD of a certain wastewater sample, by measuring the output voltage of a MFC operated by that sample, and considering all conditions of the experiments performed to obtain this model.

The correlation factor of 88% indicate the strength of the relationship between COD measurements and output voltage time for the three MFCs studied. Also, it is an indication the extent the quality of COD and output voltage measurements.

3.4. MFCs Economic Feasibility

MFCs power calculations was listed in Table **5** and the experimental data in the notes under the Table. Reviewing calculation results (in Table **5**), it was found that the maximum output power obtained in this

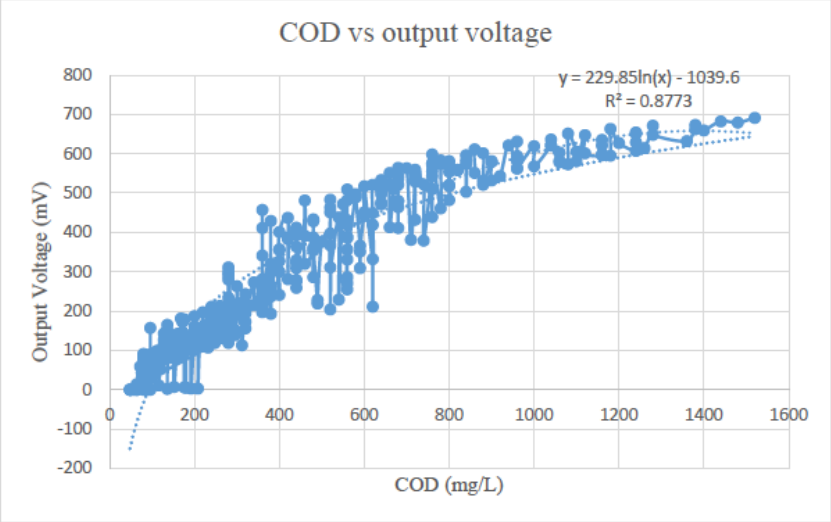

Figure 11: Relationship between COD and output voltage.

research is higher than or compatible with several previous published results ([98-103].

Estimation of the economic feasibility of output power of applying MFC technology to WWTP was done as follows:

Using the average WWTP influent flow of 11,000 m3/day or 330,000 m^3/month, the potential monthly output power monthly would be, and assuming that efficiency is 70%: the monthly output can be estimated by multiplying monthly influent by output power normalized to the volume of wastewater and assuming that efficiency is 70% as:

Monthly output power = Efficiency x flow x normalized output power

= 70% x 330,000 m^3 /month x 0.18065 kWh/m^3

= 41,730 kWh/month = 41.73 MWh/month.

Knowing that the average monthly consumed electric power in WWTP is 185 MWH/month (ranging between 130-240 MWH). So, if MFC technology apply to WWTP the purchased electricity could be reduced by 23%.

Taking the official energy cost of 0.6134 NIS/kw, the power generated by MFCs will save 41,730 x 0.6134=36,566 NIS/ month which is equivalent to $ 87,761/year;

3.5. PCR and Capital Cost Estimation

As a rough estimation of the capital cost of inserting MFCs in WWTP by estimation power to cost ratio (PCR) for the final sedimentation tank [104]. If MFCs applied to the final sedimentation tank of WWTP and Copper electrodes were used, capital cost could be estimated as listed in Table **6**.

Assuming that upscaling the WWTP system to MFC would require a reduplication of the total cost by three folds [105]. Accordingly, the total capital cost of inserting MFC system into the plant = 3 x 242,500 = $ 727,500 $

The economic feasibility of the MFC project is estimated using payback period analysis:

Payback period (years) = Investment/ Savings (per year) = 727500/ 87,761 = 8.3 years.

As the payback period of the project is more than 5 years, then the upscaling of the WWTP system to include MFC is not feasible economically. However, if we take the environmental benefits of MFC and energy challenge, upscaling of the WWTP could be considered logical and/or appropriate.

4. CONCLUSIONS

Based on the results obtained in this study, the following concluding remarks were observed:

- Fixing of optimally obtained operating parameters and varying COD concentration of the substrate revealed that a relationship exists between output voltage and COD value in MFC.
- As COD concentration of the substrate increase the kinetic model that explains the behavior of

COD decay in MFCs change from second order to first order kinetics.

- Correlation factors obtained for the four MFC groups were relatively high indicating the good quality of the data obtained
- The second order COD decay kinetic model is the most suitable model to be used to predict and explain COD variation in MFCs treating typical domestic wastewater with time.
- The first order COD decay kinetic model is suitable to be used to predict and explain COD variation in MFCs treating higher than typical domestic wastewater in concentration.
- The natural logarithmic model developed, can be used to predict MFC effluent COD concentration as a function of the MFC output voltage measured.
- The MFCs studied found not feasible economically. However, from an environmental point of view and energy perspective the MFCs could be used to solve related energy and environmental challenges.

Table 5: MFCs Power Calculations

Output power can be calculated as: P = I x V Where: P: output power, watt, I: Electrical current through the load (resistance), Ampere, V: output voltage, Volt
Electrical current can be calculated as: I=V/R Where R is the applied resistance, Ohm I=0.684/1000=0.684 mA=0.000684 A. P=0.000684 x 0.684=0.00046786 Watt. Normalized power to anode surface area = P/ Anode surface area = 0.00046786/ 0.0028 = 0.71 W/m^2 Normalized power to used volume of WW= P/volume = 0.00046786/ 0.0008 = 0.585 W/m^3.
Output power during 30 days of MFCs operation, Output power for 30 days = 0.2509 W/m^3 x 30 days x 24 hr/day = 140.4 Wh =180.65 WH/m^3.

Notes:
Anode surface area was 28 cm^2= 0.0028 m^2
Used Resistances were 1000 ohm
Maximum output voltage achieved in this study was 0.684 volt.
Average output voltage during 30 days of MFC operation was 448 mV
The average output power of P= 0.000201 W and
Normalized power per volume is 0.2509 W/m^3,

Table 6: MFC Capital Cost Estimation Using PCR

Basic costs of MFC Cost of (7 cm x 4 cm)-copper= 15 NIS= $ 4.6. Cost of salt bridge= 15 NIS= $ 4.6. Cost of containers= 30 NIS= $ 9.2. Cost of aerator= 35 NIS= $ 10.7. Cost of shaking system= 37 NIS= $ 11.35. Cost of temperature control system=33 NIS= $ 10.1. Cost of electrical connections= 4.5 NIS= $ 1.4. Total cost= $ 51.95.
power to cost ratio (PCR) = P/Total Cost =)=0.201 mW/51.95$= 0.004 mW/$
By proportion, the final sedimentation tank would be equivalent to 3859 m^3/o.ooo8 m^3-MFC = 4824 MFC
The power produced if the final sedimentation tank worked as MFC 0.201 mW/MFC x 4824 MFC =970 mW
Estimated operation cost= Produced power/PCR= 970/.004= $ 242, 500.

Notes:
Average output power= 0.000201 W= 0.201 mW.
WWTP final sedimentation tank (volume=3859 m3) to be used for one MFC:

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