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Understanding the sustainability niche of continuous flow tubular microbial fuel cells on beef packing wastewater treatment

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ABSTRACT

Beef packing industry consumes a large amount of water and energy to support its production. To transform this industry to be more sustainable, the produced wastewater from a Midwestern beef packing plant was treated by a bench-scale tubular microbial fuel cell (MFC) in continuous fed mode in present study. When the MFC was fed with 1 g L^{-1} beef extract solution, a maximum current density of 8.8 ± 0.2 A m^{-3} and organics removal of 28.2 ± 5.9% were observed. Switching feeding solution to real beef packing wastewater did not change system performance considerably. The current density achieved was 8.4 ± 0.2 A m^{-3} and the organics removal was 35.9 ± 9.7%. Life cycle assessment (LCA) results on operational phase showed that the environmental impact of produced electricity from MFC is minimal compared to the overall electricity consumption. Comparing to the existing on-site treatment infrastructures, adding MFC could reduce global warming by 36%. Also, integrating MFC into the existing on-site wastewater treatment will be less beneficial for fossil fuel depletion due to the less biogas produced, leading to higher requirement of natural gas utilization for heating purpose. The attractiveness of adding alternative energy producing treatment systems to food processors may be based on biogas production and use patterns.

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1. Introduction

As the demand of beef consumption, a great amount of beef industry wastewater are produced in the United States (Perez-Martinez et al., 2018; Li et al., 2018). In typical beef packing plants, processes such as carcass washing, antimicrobial interventions, viscera processing, and facility cleaning produce large pollutant loads that negatively impact on the environment if not treated properly (Ziara et al., 2018a). Currently, beef packing wastewater is treated using technologies similar to those used to treat municipal wastewater, including physicochemical processes (1st stage) to remove settable solids and biological processes (2nd stage) to remove organic contaminants (Bustillo-Lecompte and Mehrvar, 2015). Such integrated unit operations offer an efficient solution for contaminant removal, however the major shortcomings such as high amount of energy input (e.g. 6.9 kWh for treating slaughterhouse wastewater per ton of live cattle weight) (Li et al., 2018) and sludge production can lead treatment systems to become cost intensive and thus there is a value in considering potential alternatives. An alternative treatment approach is to apply microbial fuel cells (MFC) to recover energy. This study explores the energy recovery from beef processing wastewater using MFCs and compares the potential life cycle environmental impacts of a MFC to an existing treatment system.

MFCs are a promising approach to treat wastewater with bioenergy recovery. In MFCs, organic matter is degraded, and electrons are produced via interaction between microbial activity and solid electron acceptors/anodic electrode in anodic compartment and then the produced electrons are transferred via external circuit to facilitate reduction reaction occurred in cathodic compartment (Fig. 1A) (Li et al., 2014; Logan et al., 2006). Until now, various types of food wastewater have been examined extensively from bench-scaled reactors (Ziara et al., 2018b). For example, one previous study demonstrated that cheese wastewater could be successfully treated with 80% organic contaminants removal in a tubular MFCs (Kelly and He, 2014). Also, Lu et al. (2017) reported to operate a 20-L MFC system by feeding brewery wastewater for nearly one year with about 95% organic removal. Produced wastewater from

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Nomenclature

BOD	Biological Oxygen Demand
CEM	Cation Exchange Membrane
CE	Coulombic efficiency
DAF	Dissolved Air Flotation
FOG	Fat, Oil and Grease
HRT	Hydraulic Retention Time
LCA	Life Cycle Assessment
MEC	Microbial Electrolysis Cell
MFC	Microbial Fuel Cell
OCV	Open Circuit Voltage
OLR	Organic Loading Rate
Pt/C	Platinum/Carbon
sCOD	soluble Chemical Oxygen Demand
TCOD	Total Chemical Oxygen Demand
WWTP	Wastewater Treatment Plant

vegetable oil industries was also investigated in a two-chamber MFC (Firdous et al., 2018). The maximum voltage generation of 5839 mV was observed with organics removal of 80–90% at 35 °C.

However so far, only very limited number of publications have reported using MFCs to treat wastewater from the meat processing industry, which is a waste stream typically with a high amount of biodegradable organic compounds (e.g. the range of BOD is 150–8500 mg L^{-1}) (Bustillo-Lecompte and Mehrvar, 2017). One pioneering study reported that organics in the meat packing wastewater can be degraded with electricity generation of 80 mW m^{-2} in a single chamber MFC (Heilmann and Logan, 2006). Later, slaughterhouse wastewater was fed in a dual-chamber MFC and maximum power was generated at 578 mW m^{-2} (Katuri et al., 2012). One recent publication revealed that simulated slaughterhouse wastewater could be treated in an integrated tubular MFC with up to 99% organic contaminants removal and power generation of 165 mW m^{-2} (Ismail and Mohammed, 2016). Obviously, such early efforts offer a novel sustainable approach to treat waste stream from meat processing plants, however systematic-level studies that involving the nexus between technical gains and potential ecological concerns have not been produced. Given the qualities of such wastewater could be easily varied by the fluctuating pH and shock loadings, it is our belief that constructing an MFC system with low structural complexity and high operational resilience should be a key to apply this emerging technology to meat processing industry. In one previous study, two 4-L tubular microbial fuel cells (MFCs) were installed in a municipal wastewater treatment facility and operated for more than 400 days. The results demonstrated a high system resiliency when the anodic compartment was emptied for 1–3 days or system was operated with different HRTs (Zhang et al., 2013). Therefore, driven by this early study, tubular shape MFC was selected in current research work to further study the system's capability to handle the fluctuation when the meat processing wastewater was treated.

Life cycle assessment (LCA) has been recognized as a tool to quantify environmental impacts of a system from a life cycle perspective (Finnveden et al., 2009). Foley et al. (2010) compared the environmental benefits from anaerobic treatments, microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) and concluded that MECs provide significant environmental benefits through the displacement of chemical production by conventional approaches, although the underlying assumption that current generation of 1000 A m^{-3} is not easy to achieve. However, no studies concentrate on investigating the potential environmental benefits of MFCs as on-site treatments on the produced food processing wastewater.

To examine the potential of MFC in treating beef packing wastewater, a liter-scale tubular MFC was developed and operated to treat both synthetic and actual beef packing wastewater under varied operational conditions for about 130 days. This is the first study in the available literature that systematically investigated the feasibility of using tubular MFC to treat the meat processing wastewater in continuous operational mode. The objectives of the current study are (1) to examine the feasibility of electricity generation and beef packing wastewater treatment by using a liter-scale tubular MFC; (2) to understand the optimal system performance on electrical energy recovery, organic contaminants and nutrients removal by adopting different organic loading rates (OLRs), in hoping to better simulate varied wastewater characteristics in real beef packing practice; (3) to study the associated environmental benefits via LCA on a representative Midwest beef packing plant. It was anticipated that new information from the current study could offer new perspectives on enhancing the sustainability of beef industry in US by adding the MFCs to the existing on-site treatment infrastructure. The results from LCA are expected to provide more insights on finding the proper technical niche of MFC to beef industry by understanding the technical gains against the associated environmental impacts.

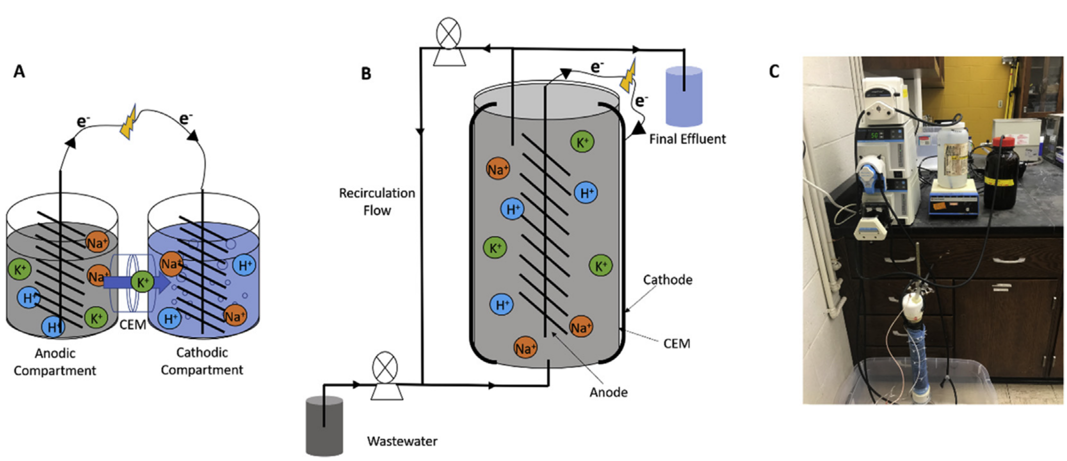

Fig. 1. The schematics of the MFC: (A) typical two-chamber MFC; (B) tubular liter scale MFC used in present study; (C) constructed module.

2. Materials and methods

2.1. Feeding solution

Three different types of wastewater, including two synthetic solutions (sodium acetate and beef extract) and one meat processing wastewater were used in present study. To obtain robust biofilm, sodium acetate was used as sole carbon source until the reactor reached the stabilization phase. Prior to feeding actual meat processing wastewater, beef extract (MP Biomedicals, Solon, OH) solution was used as a simulant to real meat processing wastewater, to avoid any culture shock issues. Meat wastewater samples used in this study were collected from a medium-size beef packing plant located in the Midwest of the US. The samples were collected from the dissolved air flotation (DAF) effluent, a treatment process usually used to remove suspended matter such as fat, oil and grease (FOG) or solids from wastewater. This wastewater source location was selected to minimize the operational complexity (e.g. clogging issue) for MFC. The wastewater characteristics are listed in Table 1. In brief, centrifuging the wastewater at 5000x rpm did not help on alleviating the concentrations of organics (e.g. total chemical oxygen demand (COD) and sCOD) and nutrients, but the turbidity was reduced from 638.67 ± 7.85 to 439.00 ± 35.22 NTU.

2.2. Reactor construction

The MFC was constructed as a tubular reactor (48 cm long and 5 cm in diameter) made of cation exchange membrane (CEM – Ultrex CMI 7000, Membrane International, Inc Glen Rock, NJ, USA) (Fig. 1B). The carbon brush with total brush part length of 56 cm and diameter of 3.8 cm (ZOLTEK Corp., Bridgeton, MO, USA) was treated by heating at 450 °C for 30 min and soaked with acetone overnight to remove impurities. The carbon brush was folded and used as anodic electrode. Net anodic liquid volume was 930 mL. Plain carbon cloth (E-TEK Inc.) was used as cathodic electrode material. Before use, both electrode materials were soaked in acetone solution overnight and rinsed several times with tap water and then heated for 30 min at 450 °C (Wang et al., 2009). Pt/C powder was used as catalyst and loaded with a rate of 0.2 mg Pt cm^{-2} on the surface of carbon cloth by brushing. The cathodic electrode was wrapped around the membrane tube and was exposed in air by using oxygen as the electron acceptor. The anodic and cathodic electrodes were connected by using titanium wires to an external resistor (27Ω).

2.3. Operation conditions

The MFC anodic compartment was inoculated with anaerobic digester sludge from local wastewater treatment plant (Theresa Street Water Resource Recovery Facility, Lincoln, NE, USA) and was operated at room temperature of ~20 °C. Synthetic solution contained (per L of DI water): sodium acetate/beef extract powder 1 g; NH_4Cl 0.15 g; NaCl 0.5 g; $MgSO_4$ 0.015 g; $CaCl_2$ 0.02 g; KH_2PO_4 0.53 g; K_2HPO_4 1.07 g and 1 mL trace element (He et al., 2006). The anolyte was recirculated at 20 mL min^{-1}. Phosphate buffer solution (PBS), which contained 107 g of K_2HPO_4 and 53 g of KH_2PO_4 per liter of DI water, was used as catholyte to rinse the cathodic electrode from top to bottom and additional tap water was added periodically to compensate for evaporation.

During the start-up period, acetate was used as a sole carbon source and external resistance was changed from 1000 to 10 Ω in a stepwise mode to obtain robust biofilm on the anode surface. After the MFC reached a steady state by observing stable voltage generation, the acetate solution was fed continuously by a peristaltic pump at a hydraulic retention time (HRT) of 15 h until Day 28. Then, 1 g L^{-1} of beef extract solution was fed as a simulation of real beef wastewater and the MFC was operated at HRT of 15 h from Day 29–35, 25 h from Day 36–48, and 77 h from Day 49–60. Beef packing wastewater, which was collected after dissolved air flotation (DAF), was used as feeding solution from Day 61. The MFC was subsequently operated at HRTs of 77, 25 and 15 h. Last, to gain a better understanding on the associated environmental benefits, the MFC system was changed to be operated in hydraulically relay mode that the feeding solution was treated in the anodic compartment first at HRT of 25 h, then the treated effluent was used as rinsing solution to the cathodic electrode, in hoping that the residual contaminants could be further treated by the attached aerobic biofilm on the cathode surface. No anodic recirculation flow was applied under this operation.

2.4. Measurement and analysis

The voltage was recorded every 5 min by a digital multimeter (2701, Keithley Instruments, Cleveland, OH). The current and power densities were normalized to the anode liquid volume. The pH was measured using a benchtop pH meter (Thermo Scientific Waltham, MA, USA). The conductivity was measured by a benchtop conductivity meter (Hach Company, Loveland, CO, USA). The chemical oxygen demand (COD), ammonium and nitrate concentrations were measured according to the manufacturer's procedure (Hach Company, Loveland, CO, USA). Polarization curve was performed by reducing external resistance from 1000 to 4.7 Ω in a stepwise mode and the voltages generated in each condition were recorded after the system reached to steady state. Coulombic efficiency (CE) was calculated based on the ratio of total charge produced in electricity and the theoretical charge produced from the removed COD, according to a previous study (Ge et al., 2013).

Table 1
Characteristics of beef extract (B.E) solution and industrial wastewater collected after dissolved air flotation (DAF) unit.

	Unit	B.E	DAF	DAF*
pH	–	7.2 ± 0.0	7.0 ± 0.0	6.9 ± 0.0
Conductivity	mS cm^{-1}	3.3 ± 0.1	2.2 ± 0.0	2.1 ± 0.0
Total COD	mg L^{-1}	1357.6 ± 78.6	2941.7 ± 16.5	2915.0 ± 272.9
Soluble COD	mg L^{-1}	1337.3 ± 58.3	1506.7 ± 33.0	1626.7 ± 29.0
Turbidity	NTU	4.1 ± 0.0	638.7 ± 7.9	439.0 ± 35.2
Total Suspended Solids (TSS)	mg L^{-1}	2.7 ± 0.2	484.2 ± 6.9	387.3 ± 88.7
NH_3–N	mg L^{-1}	9.6 ± 0.2	66.0 ± 3.1	65.9 ± 2.4
NO_3–N	mg L^{-1}	U.D	1.3 ± 0.1	1.3 ± 0.1
PO_4^{3-}	mg L^{-1}	U.D	110.0 ± 2.9	107.3 ± 1.3

Note: B.E represents beef extract solution; DAF represents the DAF effluent fed to MFC that was the supernatant after settling (no centrifuging); DAF* represents the DAF effluent fed to MFC was centrifuged at speed of 5000 rpm prior to use. U.D represents the values are under detection limit.

$$CE = \frac{Q_{out}}{Q_{in}} = \frac{8It}{Fq\Delta COD} \quad (1)$$

where Q_{out} (Coulomb) is the produced charge, Q_{in} (Coulomb) is the total charge available in the removed organic compounds, I (A) is the average current within time t (s), F is the Faraday's constant, q is the feeding rate (L day^{-1}), and ΔCOD is the COD (mg L^{-1}) removed within time t.

2.5. Environmental impact assessment

To gain a better understanding of the potential advantages of using MFCs, life cycle assessment was employed by SimaPro software (Version 8.4, PRé Consultants, The Netherlands) to quantify the environmental impacts of beef packing wastewater treatments from two scenarios. Scenario 1 (existing treatment) includes treatment processes of dissolved air flotation (DAF), lagoon, mixing tank, aeration tank, clarifier and chlorine disinfection; Scenario 2 (proposed new system with MFC) is like Scenario 1 with an addition of MFC after DAF to form an integrated system. Also, to understand the influence of reutilizing biogas on site, two biogas reutilization practice (100% and 0%) were studied on each scenario, named as S1a, S1b, S2a and S2b (a denotes 100% biogas reutilization; b denotes as 0% biogas reutilization).

The information about system boundaries can be found in Fig. 2. The functional unit of the study was defined as treating 1 m^3 of beef packing wastewater (DAF effluent) to reach same final effluent characteristics from a beef packing wastewater treatment plant including final BOD of 5.90 mg L^{-1}, ammonium-nitrogen of 0.32 mg L^{-1}, total suspended solids of 12.20 mg L^{-1} and total phosphorus of 18.00 mg L^{-1}. The life cycle inventory of resources, energy, and wastewater was modeled for each scenario. The inventory data specific to this study, including energy use, chemical requirements, and sludge treatment about existing on-site treatment facility (Scenario 1) were collected through plant visits and consultation with plant operators (Li et al., 2018). The inventory data related to MFC (Scenario 2) was obtained from the experiment of this study. The detailed inventory information of two scenarios can be found in Table 2. Databases of US-EI 2.2 and Ecoinvent version 3 provided in the SimaPro software were chosen as background databases to cover environmental impacts caused by indirect processes. The environmental impacts were characterized by using Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) developed by the U.S. EPA (Bare, 2012).

To simplify the complexity of this preliminary LCA work, we only focused on studying the associated environmental impacts from operational phase. Previous WWTP LCA research efforts proved that comparing to operational phase, the environmental impacts from construction phase are minimal (Renou et al., 2008; Smith et al., 2014). Also, it is worthy to note that only five environmental impacts, including ozone depletion, global warming, eutrophication, carcinogenic, and fossil fuel depletion were presented and discussed in the main context, since these five impacts are most correlated to the addition of MFC.

3. Results and discussion

3.1. Polarization curve

Polarization curve is a tool to analyze and characterize the performance of fuel cells (Logan et al., 2006). A polarization curve represents the voltage and power as a function of current density (Fig. 3). Typically, polarization curve includes three segments along with decreased voltage. Segment A starts from open circuit voltage (OCV) and shows voltage drop occurring due to the activation loss. Segment B is where the voltage drops slowly and linearly with increasing current generation; the ohmic loss plays a dominant role in this zone. For the MFC, the internal resistance can be obtained from the slope of segment B and maximum power is achieved when the external resistance equals to internal resistance. In this study, varied external resistors (1000−4.7 Ω) were used and the corresponding voltages were recorded after the system reached to steady state conditions when the MFC was fed with acetate solution. It was shown that maximum current of 18.0 A m^{-3} can be generated along with treating wastewater and the internal resistance was 27 Ω (Fig. 3). Segment C is another fall of voltage at higher current due to the poor mass transfer rate (Logan et al., 2006). Therefore, the MFC was operated with 27 Ω external resistance

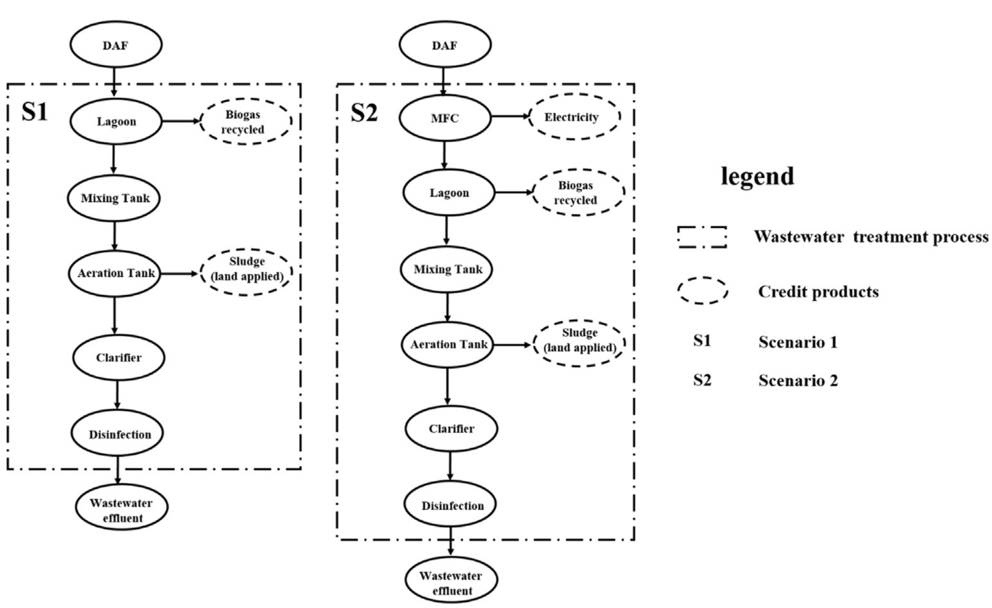

Fig. 2. System boundaries of two scenarios of wastewater treatment process analyzed by life cycle assessment; DAF: Dissolved Air Flotation; MFC: Microbial Fuel Cell.

Table 2
Resources inputs and emissions associated with a typical industrial anaerobic wastewater treatment plant (WWTP) (Scenario 1) and proposed new system (Scenario 2) for treating 1 m3 beef packing wastewater.

	Scenario 1	Scenario 2	Unit	Data Source
Resource Input				
Electricity	1.29	0.98	kWh m^{-3} wastewater	Plant record, 2016
Chlorine	18.41	18.41	g m^{-3} wastewater	Plant personnel
Sodium Hydroxide	0.01	0.01	g m^{-3} wastewater	Plant personnel
Sodium Hydrogen Sulfite	0.02	0.02	g m^{-3} wastewater	Plant personnel
Polyacrylamide Polymer	0.10	0.10	g m^{-3} wastewater	Plant personnel
Emissions				
BOD_5, Effluent	5.90	5.90	g m^{-3} effluent	US EPA, ECHO 2016
TSS, Effluent	12.2	12.2	g m^{-3} effluent	US EPA, ECHO 2016
NH_3, Effluent	0.32	0.32	g m^{-3} effluent	US EPA, ECHO 2016
Phosphorus, total as [P]	18.00	18.00	g m^{-3} effluent	US EPA, ECHO 2016
Sludge	514.35	268.00	g dry solids m^{-3} wastewater	Plant record, 2016
Biogas flare	18.18	9.48	MJ m^{-3} wastewater	Plant record, 2016
Avoided Products				
Natural gas	19.50	10.16	MJ m^{-3} wastewater	Equivalent calculations
Fertilizer $(NH_4)_2HPO_4$	75.87	39.55	g m^{-3} wastewater	Equivalent calculations

Note: The electricity means overall electricity consumption supplied from power grid. Sludge is assumed to be linearly correlated to the organic strength of waste stream. Natural gas (avoided products), the values are based on scenario (a) that the recycled biogas was performed with 100% efficiency. Fertilizer production is assumed to be linear to the nitrogen centration in the wastewater.

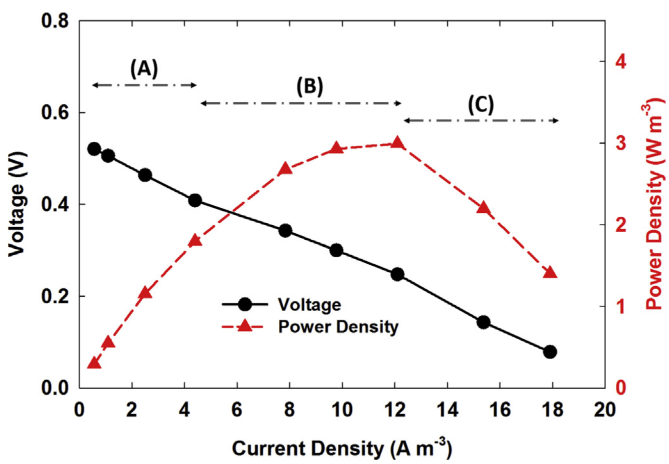

Fig. 3. The polarization curve for the MFC: Solid black line is for voltage and dashed red line is for power output. Segment A indicates voltage drops at low current region due to the activation loss; segment B indicates voltage drops due to the ohmic loss; segment C indicates voltage loss at high current region due to the limited substrate transfer.

afterward.

3.2. MFC fed with synthetic wastewater

The MFC was fed with synthetic solutions until Day 60 and the organic contaminants removal and electricity generation results are presented in Fig. 4. The system performance was demonstrated by examining its electricity generation and organic contaminants removal. Sodium acetate was used as organic source at HRT of 15 h until Day 29. During this period, the MFC produced a current density of 9.9 ± 0.6 A m^{-3} (Fig. 4A). On Day 19, adding 50 mL of 1 M fresh buffer solution to catholyte tank led to a temporary increase in current generation, indicating the accumulation of hydroxide ions which can limit system performance; periodically replacing catholyte is preferred to maintain an efficient cathodic reaction.

Since the goal of this study was to investigate the system performance for treating beef packing wastewater, minimal COD data was collected during the initial sodium acetate start-up period. On Day 30, 1 g L^{-1} beef extract solution was used as organic source and fed at three different HRTs in a stepwise fashion. Beef extract was

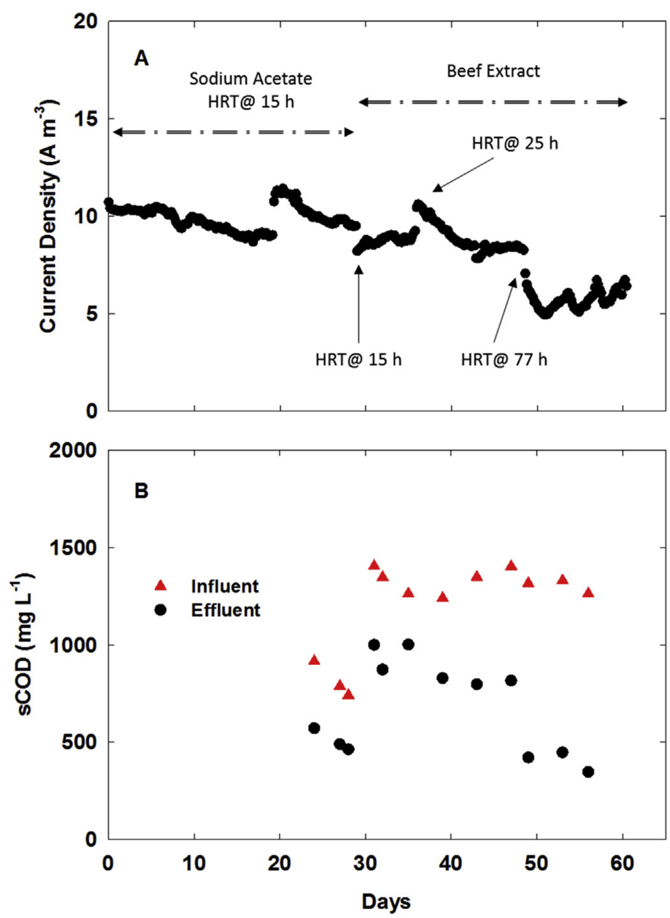

Fig. 4. The performance of the MFC with the synthetic solution: (A) electricity generation; (B) the COD removal.

chosen to simulate real wastewater stream from beef packing plant. From Day 30–35, the MFC was operated at HRT of 15 h and the current generation was 8.8 ± 0.2 A m^{-3}, which is significantly lower ($p < 0.05$) than the previous operation with sodium acetate, because the beef extract is more complex and requires longer time to be degraded than acetate. Further increasing the anodic HRT to

25 h did not affect current generation ($p > 0.05$); however, a reduced current generation of 5.7 ± 0.5 A m^{-3} was observed after the HRT was changed to 77 h, which was significantly lower than previous two operations with shorter HRTs ($p < 0.05$), most likely due to a reduced organic loading and lower bulk organic concentration were formed at longer HRT and as a result, limited organics diffusion and weakened mass transfer occurred within anodic compartment. According to the well-established two population theory, only two microbial consortia (e.g. electroactive bacteria and methanogens) exist in the anodic compartment while the electroactive bacteria was commonly assumed to grow as biofilm and attach on the electrode surface only (Pinto et al., 2010). In the present study, the anodic electrode was located at the center of the anodic compartment, therefore at longer HRT, organics could become less available to the electroactive bacteria due to the weakened mass transfer mechanism and as a result, poorer electrical performance was observed.

The organics removal was measured as soluble COD (sCOD) (Fig. 4B). When it was operated at HRT of 15 h with acetate as carbon source, the MFC removed 37.6 ± 0.1% of sCOD, indicating a need for extended retention time to achieve more complete organic removal. The coulombic efficiency was calculated as 14.9%, indicating that microbial competitions occurred on organic degradation and the performance of electroactive bacteria played a minor effect on the overall organic removals. Switching feeding solution to Beef Extract at HRT of 15 h, the system performed relatively lower on both COD removal and CE. For example, by changing feeding solution to beef extract, COD removal of 28.2 ± 5.9% was observed at HRT of 15 h with CE of 10.7%, which both are lower than operation with sodium acetate at same HRT. Possible reasons could be that (1) beef extract compounds need longer time to be completely degraded and retention time of 15 h might be too short for organics to reach to electroactive bacteria prior to discharging; (2) Methanogens could form more robust flocs and become more competitive within the anodic compartment.

To further study the influence of HRT on system performance, three different HRTs were examined when the MFC was fed with Beef Extract solution. It showed that effluent COD decreased significantly along with extended HRT, whereas the improvement of CE was relatively low. For example, higher COD removal of 38.6 ± 3.9 and 69.0 ± 2.6% were achieved when the MFC were operated at HRT of 25 and 77 h respectively and the corresponding CE were increased to 13.3 and 14.6%. These findings demonstrated that high organics removal performance in MFC does not necessarily output high electrical performance due to the low conversion efficiency between chemical energy embedded in wastewater and extracted electrical energy from treatment process.

3.3. MFC fed with beef packing wastewater

To gain a better understanding on the feasibility of using tubular MFC to treat beef processing wastewater, which were collected from a Midwestern beef packing plant on bi-weekly basis. The wastewater samples were collected after the pretreatment including screening and dissolved air flotation (DAF). To have a better comparison between synthetic and real wastewater samples, the COD removal and current generation of the system is presented in Fig. 5.

Given the complexity of DAF effluent, the MFC was fed at HRT of 77 h starting at Day 61. Current generation of 5.1 ± 0.7 A m^{-3} was observed, which is comparable to current generation with beef extract at same HRT. Further decreasing HRT could considerably enhance current generation. For example, by changing HRT to 25 h, the current generation increased to 6.4 ± 0.4 A m^{-3}. Further reducing HRT to 15 h enhanced current generation to 8.4 ± 0.2 A m^{-3}, significantly higher than other two operations ($p < 0.05$). It is noteworthy that comparing to system performance with beef extract at HRT of 15 and 25 h, the current generation of MFC with real beef packing wastewater are correspondingly low ($p < 0.05$) and possible reason is because of the different complexities of two feeding solutions.

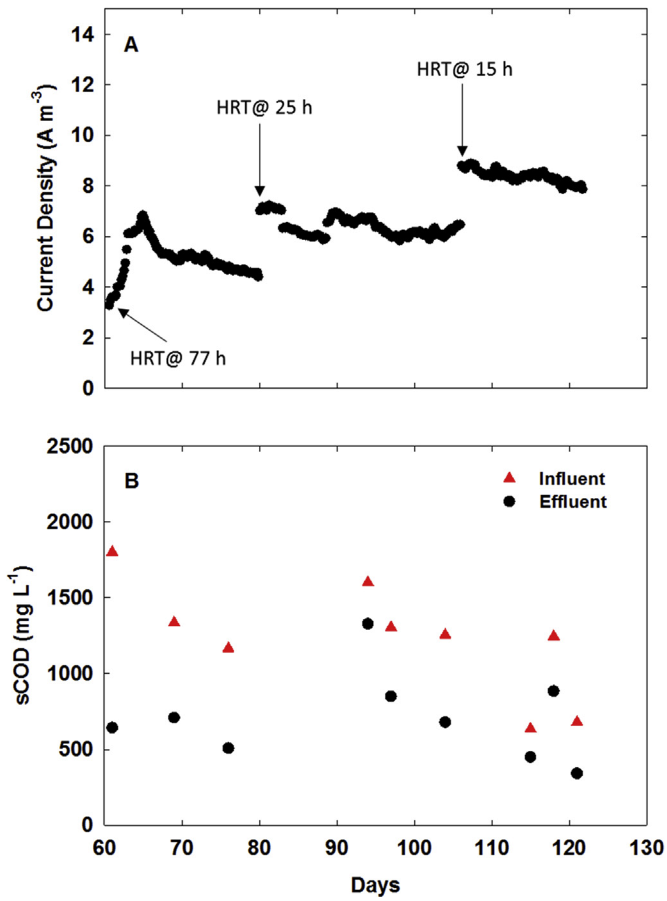

Fig. 5. The performance of the MFC with the real beef packing wastewater: (A) electricity generation; (B) the COD removal.

Organic removal performance was significantly related to HRTs as well. At HRT of 77 h, about 55.8 ± 7.1% of organic contaminants were removed from real beef wastewater, which was significantly higher than other two operations with shorter HRTs ($p < 0.05$). Comparing to the beef extract, the MFC performed poorly on organics removal at HRT of 77 h, possible reasons could be the complex constituents of real beef wastewater that required longer time to reach complete degradation than more homogeneous beef extract solutions, since parts of organics in DAF effluent may not be degraded readily. By changing HRT to 25 h, the organic contaminants removal were reduced to 40.3 ± 5.5% that is comparable to beef extract at same HRT ($p > 0.05$). Further reducing HRT to 15 h, the organics removal from real beef wastewater decreased to 35.9 ± 9.7%, which was also not significantly different than beef extract at the same HRT ($p > 0.05$), indicating that both feeding solution behave similarly on degradation easiness at short HRTs. The results from running real beef wastewater by varying HRTs also demonstrate that other treatment method (e.g. membrane separation) might be integrated with MFCs to help improving the overall treatment performance, especially when the systems are operated in long HRT mode.

3.4. Environmental assessment

Life cycle assessment (LCA) has been used extensively as a tool to quantify environmental impacts associated with all stages of a product or system from raw materials extraction to end-of-life treatment (Roy et al., 2009). In present study, the environmental impacts were examined by comparing the difference of inputs and outputs between two different scenarios (as illustrated in Fig. 2): (a) Scenario 1 was an on-site treatment system from a local beef packing plant and (b) Scenario 2 was a proposed new system by adding MFC to the existing treatment processes. It is noteworthy that from our personal communications with plant operators, we found that varied strategies of using produced biogas on site were employed mainly because (1) less biogas is used during the summertime for process heating; (2) when the content of corrosive hydrogen sulfide (H_2S) reaches high concentration, the produced biogas was discarded to protect energy conversion equipment. Thus, in our LCA models, to gain a better understanding on the environmental advantages of the proposed system, two biogas (recycled) reuse efficiencies were considered with footnote a and b represent 100 and 0% biogas reuse. It was determined through the personal communication with plant operator, the produced biogas usually was consumed via two pathways, including (1) flared and (2) consumed on-site for water heating (replacing natural gas usage). Also, as already mentioned in Section 2.5, the qualities of raw wastewater and final effluent were assumed to be same in all studied cases.

In LCA analysis, the system performance was studied and used as key input parameters. To reduce the overall environmental impacts, the MFC system was changed hydraulically, in which the feeding solution was fed and treated within the anodic compartment first, then the treated effluent was flowing out and rinsed cathodic electrode by gravity before collected by a waste jar underneath the MFC. In this way, the organics can be biodegraded more extensively via the attached biofilm on the surface of cathodic electrode and no electrical energy is required to recirculate the catholyte solution to rinse the cathodic electrode. The current density of 5.6 ± 0.6 A m^{-3} and organics removal of $44.5 \pm 10.3\%$ can be achieved at HRT of 25 h (Fig. S1).

The environmental assessment data of five selected categories were summarized in Fig. 6. To understand the relative weight of each input component, percentage contribution was shown on y-axis in Fig. 6. The results of global warming potential and ozone depletion in this work are reported as 2.4–4.5 kg CO_2 and $3.5*10^{-8}$ to $3.9*10^{-8}$ kg CFC-11 eq per m^3 wastewater among the four scenarios, respectively. Those results are on the similar magnitude with results reported in other MFC studies in the literature. For example, Zhang et al. (2018) reported the global warming potential and ozone depletion at the operational stage of a 10 W/m^3 MFC are 4.1 kg CO_2 and 2.6 kg CFC-11 eq per m^3 (Zhang et al., 2018). It was found that the overall eutrophication was not changed by adding the MFC. The reason for such minor difference is because the wastewater effluent quality plays a significant role (91%) on the eutrophication impact, while the pertinent assumption about same qualities on final effluent does not generate any discrepancy. The only difference on the overall eutrophication impact in studied scenarios is mainly due to (1) nutrients recovery; and (2) sludge disposal. Since adding MFC could reduce the overall sludge production, as a result, fewer nutrients may be recovered as phosphorus fertilizer, and less sludge wastage requires disposal in Scenario 2. Likewise, there is unnoticeable change of Ozone Depletion in four studied scenarios. From Fig. 6, chlorine gas usage plays a dominant portion on the overall Ozone Depletion, and same amount of disinfectant was assumed to be used in studied scenarios due to the negligent effect of MFC on disinfection.

The embedded environmental impacts from wastewater treatment could also have a notable contribution to the human health (Li et al., 2019). On carcinogenic impact, adding MFC does not necessarily reduce the overall carcinogenic impact (Fig. 6). Chlorine Gas and Sludge Disposal are two major factors in this category, as shown in Fig. 6. Thus, adding MFC (Scenario 2a and 2b) could theoretically leads to less carcinogenics impact due to the lessen load of sludge disposal. However, this may not be the case in present study. The SimaPro inventory analysis shows that heavy metals such as Chromium, Mercury, Nickel, Cadmium, Lead and Arsenic altogether generates 99.6% of carcinogenics impact in

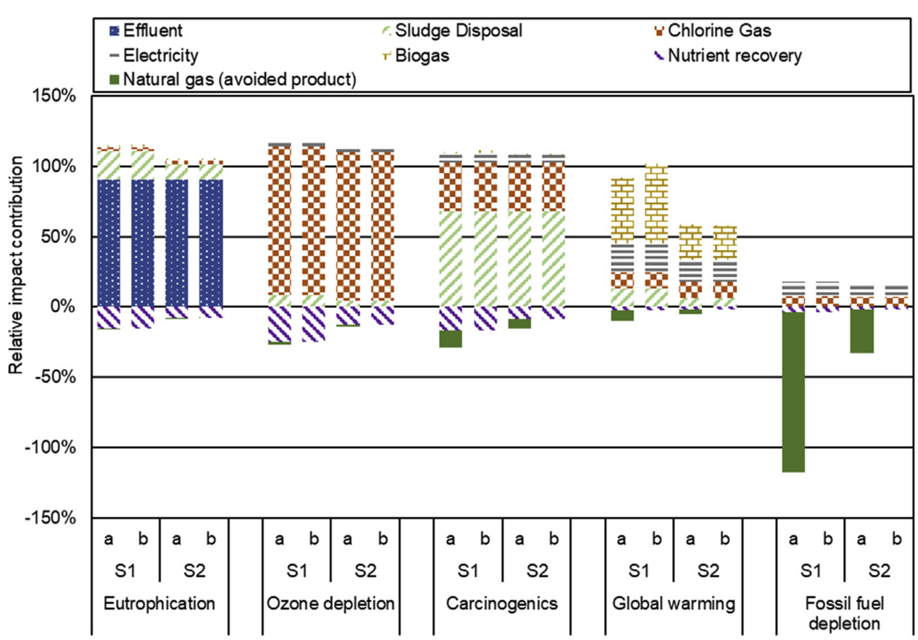

Fig. 6. Five environmental impacts selected from TRACI impact categories for two scenarios. Scenario 1 (S1): existing on-site wastewater treatment system; Scenario 2 (S2): integrated MFC with existing on-site wastewater treatment system. Letters a and b on each scenario designate that the produced biogas (Re) are used on site and flared, respectively.

sludge disposal (data not shown). Due to the limitation of MFC on heavy metal removal, the scenario 2 had similar carcinogenic impact results.

Considerable difference in global warming also exists between the studied scenarios (Fig. 6). In general, adding MFC (Scenario 2a and 2b) could reduce the total global warming impact since less biogas was flared from less sludge production. This is reflected from Fig. 6. Chlorine Gas, Biogas and Sludge Disposal are three major contributing components to global warming impact. In Scenario 2 (adding MFC), less organic matters remain in the waste stream to be treated by the subsequent anaerobic and aerobic processes, thus less biogas is flared, and less sludge is available for land application.

Fossil fuel depletion, another factor could lead to significant environmental impact if massive amounts of energy are used. Natural gas has been used extensively as the heating source for US plants and as a result, its usage serves as an indicator on fossil fuel depletion. Thus, using biogas on site for heating purpose (Scenario 1a and 2a) could reduce fossil fuel depletion. It should be noted that for fossil fuel depletion in Fig. 6, more negative value indicates less external energy is required and the overall operation is more environmentally friendly. Using 100% recycle efficiency on produced biogas (S1a and S2a) could produce negative impact on fossil fuel depletion, indicating using the biogas on-site for heating purpose could be helpful for reducing non-renewable fossil fuel resource. However, flaring all the produced biogas (S1b and S2b) produced more positive impact on fossil fuel depletion, indicating more natural gas is required from outside source to run the plant's overall operation. Moreover, it is interesting to note that adding MFC (S2b) (−31% of S1a) has minor effect on improving the fossil fuel depletion than S1b (−35% of S1a). This result demonstrated that the fossil fuel depletion is more correlated to the strategy on using produced biogas on site. Flaring all the produced biogas yield similar impact between the existing on-going practice and the proposed integrated system.

3.5. Perspectives

The current manner of producing food products has a large impact on the environment and there is a desire to identify more sustainable ways to operate food processing systems (van der Goot et al., 2016). Thus, there is a critical need to establish a sustainable beef cattle production that could offer better nexus between economic development and food supply with less environmental impacts. We studied the feasibility of using MFC as a novel approach to treat beef packing wastewater and new findings from current study are expected to provide more insights to other food processing practitioners on disposing the produced wastewater with less environmental impacts. We also expect these new findings could shed lights to other similar industries that also produce high strength wastewater such as paper manufacturing etc.

New findings from current study might stipulate several research topics for later studies. Future research trajectories might be: (1) more cost-effective electrode could be attempted. Previous study has proven that modified electrode materials such as nitrogen-doped carbon materials could serve as an ideal alternative to regular Pt-based cathode electrode (Zhang et al., 2014), although the long-term performance of nitrogen doped electrode at large-scale application warrants a further study; (2) the qualities of MFC effluent should be further improved. Integrating other conventional wastewater treatment technologies might be solutions. For example, integrating algal bioreactor with MFC provides an approach to remove nutrients. Such an integrated system may offer extra commercial value to beef packing industry. The harvested algal biomass could be used as forage to feed the cattle (Ziara et al., 2016). (3) chlorine gas use for disinfection purpose seems play a role on overall greenhouse gas production. Finding an alternative disinfecting approach could transform the beef packing industry to be more sustainable; (4) if anaerobic digestion is used on-site to produce biogas, maximizing the use of biogas to reduce fossel fuel consumption will improve the sustainability of production; (5) integrating the advanced wastewater treatment technology (e.g. membrane technologies) with MFC might offer a solution to reduce overall on-site water usage via recycling the treated effluent; (6) upscaling MFC is a critical step. The harvested electrical energy could be stored and used to drive some simple sensors (e.g. temperature, humidity etc.) in beef packing plant.

A key finding of this study is the importance of beneficial reuse of biogas from anaerobic treatment. This study shows that when anaerobic treatment is applied, if the biogas can be beneficially used to replace natural gas, any change to the treatment system that reduces biogas production must provide significant sustainability benefits. Dramatic improvements in alternative treatment strategies (e.g., MFC, algal systems), will be required to provide large additional fossil fuel benefits to replace the lost biogas. Alternatively, for plants that either use aerobic wastewater treatment or those that flare the biogas, the use of alternative treatment strategies are much more likely to result in a net sustainability improvement. Thus, the attractiveness of adding alternative energy producing treatment systems to food processors may be based on biogas production and use patterns.

4. Conclusions

In this study, a novel approach to treat beef packing wastewater was presented. For the first time, tubular MFC system was proposed to treat high-strength wastewater from beef packing plant in continuous mode. By attempting various types of feeding solution, maximum current density of 9.9 ± 0.6 A m^{-3} was achieved when the MFC was fed with 1 g L^{-1} sodium acetate at HRT of 15 h. However, poorer electrical performance was observed by feeding real wastewater from beef packing plants, which is likely due to the higher complexity. Preliminary LCA study showed that integrating MFC with existing on-site wastewater treatment infrastructure offers environmental advantages as compared to existing on-site treatment processes in terms of global warming at all studied situations and the use of chlorine gas for disinfection purpose plays a role on overall greenhouse gas production. Fossil fuel depletion correlates closely to the frequency of using the biogas on site. Further studies could focus on investigating the feasibilities of MFCs more broadly in food processing industry and optimizing the system performance via maximizing energy recovery and minimizing the overall environmental impact.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Jian Li: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Rami M.M. Ziara:** Methodology, Investigation, Formal analysis, Writing - review & editing. **Shaobin Li:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Jeyamkondan Subbiah:** Conceptualization, Formal analysis, Writing - original draft, Project administration, Funding acquisition. **Bruce I. Dvorak:** Formal analysis, Formal analysis, Writing - original draft, Writing - review & editing, Supervision, Project administration.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.120555.

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