ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 2, Is 11 , November 2015

Energy Harvesting from Kitchen Waste through Two-chamber Microbial Fuel Cell

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ABSTRACT: In this paper, work has been done on the production of electricity from the leachate as anodic substrate obtained from kitchen waste by hydrolysis process using Two-chambered Microbial Fuel Cell (MFC) by anaerobic digestion process.Hydrolysis process was carried out by Leaching Bed Reactor (LBR).Hydraulic retention times used were 48, 36, 24, 16, 12 hours. Four different OLRs i.e. 1.0, 1.3, 2.0, 2.5 and 3.0 kg COD/m^3/d were selected for the study. At OLR 2.0 kg COD/m^3/d better substrate reduction with higher bio-energy and thus considered as the optimum loading condition of MFC with Kitchen waste as anodic fuel. The highest current 68 µA was obtained on loading rate of 2.5 kg COD/m^3/d and at HRT of 16 hours. Maximum voltage obtained was 889 mV.Maximum current density and power density was 0.346 mA/m^2 and 308.42 mW/m^2.

KEYWORDS*:* Microbial Fuel Cell, Hydrolysis, Volatile fatty acid, Power Density

I. INTRODUCTION

Global energy consumption has been increasing drastically in the past decade. The gradual depletion of fossil fuels, such as petroleum, coal and natural gas, and the environmental concerns of fossil fuel consumption have driven an intensive search for alternative energy sources. Such alternative energy sources should be hugely available, sustainable and eco-friendly [1]. Kitchen waste has attracted considerable attention in recent years from the bio-energy recovery point of view, due to its high energy potential, biodegradability and inexhaustibility [2]. Anaerobic digestion is a preferred method with several advantages, including volume reduction, waste stabilization, and biogas recovery [3]. The whole reaction is run out with the help of microorganisms and the growth of microorganisms depends on various parameters like pH, temperature, organic loading rate, reactor designing, inoculums and HRT. [4]

A microbial fuel cell (MFC) or biological fuel cell is a bio-electrochemical system that generates a current by bacterial interactions found in nature. MFC is a sustainable source of power generation [5]. Typically, an MFC reactor is designed with anode and cathode compartments separated by a proton exchange membrane or cation exchangemembrane. In the anode compartment, cationic species such as Na^+, K^+, NH_4^+, are in higher concentration than protons (H^+). These cationic species are migrated by the membrane to the cathode at a faster rate to achieve electro neutrality under MFC conditions [6]. PEM used in MFCs include Nafion, Ultrex, and salt bridge [7]. Proton exchange membrane (PEM) strongly affects the power generation in MFC. It separates the electrolyte into two chambers, is employed as an insulator for maintaining the redox potential and only allows specific ions to exchange.

The aim of present work is to study the feasibility of bioelectricity generation in dual chambered MFC, using Ultrex as proton exchange membrane (PEM), graphite rod as electrode and leachate of food waste as substrate. Performance of MFC, employing commercially available PEM, was evaluated under different organic loading rates (OLRs) and HRTs. By keeping resistance constant i.e. 100 ohms, maximum current and voltage capacity of this MFC was studied. The composite nature of food based waste, presence of proteins, oil and the size variation, influence the treatment efficiency significantly. The performance of MFC was studied based on the substrate loading rate.

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II. RELATED WORK

A typical MFC for producing electricity consists of anodic and cathodic chambers partitioned by a Proton Exchange Membrane (PEM). Microbes in the anodic chamber of an MFC oxidize added substrates and generate electrons and protons in the process. Electric current generation is made possible by keeping microbes separated from oxygen or any other end terminal acceptor other than the anode and this requires an anaerobic anodic chamber. Various studies have been carried out using different substrate, OLR's, pH etc.Canteen based composite food waste was studied using single chamber MFC. The maximum power output was observed at 1.74 kg COD/m^3 (295 mV; 390 mA/m^2[2]. Increasing power production of microbial fuel cells (MFCs) is a common research ambition. In up-flow bio-cathode microbial fuel cell (MFC). Maximum volumetric power density of 10.04 W/ m^3 was obtained at the OLR of 0.923 kg COD/ m^3 d/1[7]. Higher current density in single chamber MFC using glass wool as proton exchange membrane (PEM) was observed 98.13 mA/m^2 at OLR 2.64 kg COD/m^3/day.[8]

III. EXPERIMENTAL METHODOLOGY

A. MEDIUM AND INOCULUM SOURCE

The inoculum was obtained from working anaerobic reactor of Vasundhara Dairy, Nagpur. The amount of kitchen waste generated from an Institutional Campus Hostel mess was characterized using IS 9234-1979 and IS 10158-1982. About 400-500 students use the mess facility. The per-capita generation of kitchen waste from hostel mess was found to be 0.36 to 0.70 kg/capita/day. The anodic substrate used for this study was prepared using kitchen waste collected from mess kitchen; green vegetables were collected from vegetable market and a saw dust from local saw mill. They showed the variation in organic waste which can be observed by the wide range COD values. Density of kitchen waste was 750-830 Kg/m^3. Sawdust collected from saw mill was used as the bulking agent along with kitchen waste and green vegetables. Physical composition is shown in the Table 1.

Table 1: Physical Composition of Kitchen Waste

Sr. No.	Constituents	% value (Range)
1	Chapatti	16.4%
2	Cooked rice	29.8%
3	Salad	6%
4	Cooked vegetables	47.8%
5	Cereals	8.3%
6	Non-putrescible Materials/Miscellaneous	0.79%

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B.FUEL CELL ASSEMBLY AND OPERATION

A laboratory scale two chamber Microbial Fuel Cell (MFC) was made up of plastic bottles, containing two chambers having capacity of 1000 ml each, with working volume of 800 ml. Electrodes were of graphite material having diameter 1.8 cm, and surface area was 31.1 cm^2. The chambers were connected with (PVC) connecting assembly having of diameter 2.5 cm and having Proton Exchange Membrane (PEM) Ulterx (U.S.A) for the transfer of proton and worked as filter to the proton from anode chamber to cathode chamber. This PEM was fitted with rubber gasket to the plastic pipe assembly to make it leak-proof. An anaerobic microenvironment was maintained in the anode compartment. Cathode chamber was kept open to air for maintained aerobic condition. The two electrodes were connected by using clamp with copper wire which was considered to be the good conductor of electricity. Lower side of anode was always in contact with wastewater. Resistor (100 ohms) was connected across the circuit. The current and voltage output across the 100 Ω resistors was recorded every day with a multimeter. The schematic diagram of experimental setup of MFC is shown in Figure 1. Provision was made in design for sampling ports, input was provided from bottom and samples were collected from top. The MFC was operated at room temperature 28 ± 2°C. Operating parameters were pH, temperature, COD, Flow rate, current; voltage and resistance measured through this experimentation. For start-up of the anaerobic reactor of MFC Cell, the anode chamber filled with 600 ml of substrate containing 590 ml distilled water, 9 ml leachate and 1 ml inoculums. Theinfluent feed pH was in the range of 6-7 throughout the experiment which was considered as optimum range [7]. The MFCwas then fed with higher loading as per design of experiment with the leachate of kitchen waste obtained from hydrolysis reactor. Initially, organic loading rate was kept 1.0 Kg COD/m^3/day; with HRT 48 hr. Influent COD maintained 1000 mg/lit. Typical electrode reactions are shown below using acetate as an example substrate.

$$CH_3COO^- + 2H_2O \rightarrow 2CO_2 + 7H^+ + 8e^- \quad \ldots (1)$$

$$O2 + 4e^- + 4H^+ \rightarrow 2H_2O \quad \ldots (2)$$

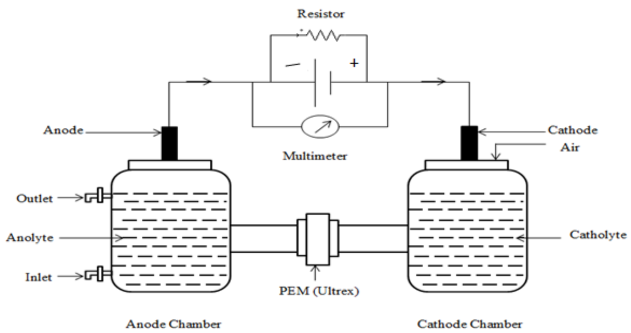

Figure 1: Schematic Diagram of Experimental Setup of MFC

C.DATA ACQUISITION

The voltage across a load (100 Ω) was measured by digital multimeter. The measured voltage was converted to current through Ohm's law (voltage = current × resistance) and to power using (Power = current × voltage). Flow was driven with flow rates between 0.69 mL/min. Data was collected on every day. The power density of the MFCs was calculated according to Eq. (3)

$$P = U \times (I / A) \quad \ldots (3)$$

Where, A = surface area of the electrode,
I = sustainable current
U = cell voltage

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IV. EXPERIMENTAL RESULTS

A. GENERATION OF LEACHATE

The quantities of leachate collected daily from all the reactors were more or less similar, in the range of 800 to 1600 ml. The quantity of input water was 2000 ml. It was observed for 20 days of operation. Volume of leachate generated against time was observed. In a leach bed study with kitchen waste, progressively increased the addition of water to the leachate bed and observed a progressively increasing volume of leachates. Increased leaching could be achieved with increasing water addition [9]. Maximum volume of leachate obtained in the duration of 10-12 days in the reactor 2 and 3, mainly due to solubilisation of solid material of kitchen waste and vegetable waste. A decrease in leachate production would be unfavourable for the soluble organic matters leaching out of LBR. The anaerobically digested sludge has a higher viscosity than water, which might contribute to the increased leaching resistance in reactor [10]. Variation in leachate quantity is shown in figure 2.

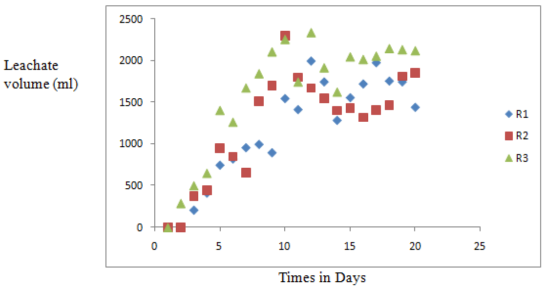

Figure 2: Variation of Quantity of generation of leachate

B.VARIATION IN VFA GENERATIONS

Volatile fatty acid (VFA's) is the key intermediate products which are obtained in the first stage of anaerobic digestion of kitchen waste [11]. The amount of volatile fatty acid concentrations in the leachates generated from acidogenic reactors are given in figure 3. The total VFA concentrations are higher during the span of 7-9 day up to 1762 mg/l in Reactor 2 and then it goes on decreasing. VFA concentrations increased gradually along with digestion, indicating the growth of acidogenic bacteria in Leaching Bed Reactor (LBR) with different levels of VFA being observed among LBRs. The increased and/or stable yield of VFA and COD of the leaching could be the result of continuous degradation of hydrolysis products [9].The pH in all the reactors was found to be in the range of 4-6 which is in the desirable range for acidogenesis. The study reveals that the production of VFA increases with increase in digestion time irrespective of pH value.

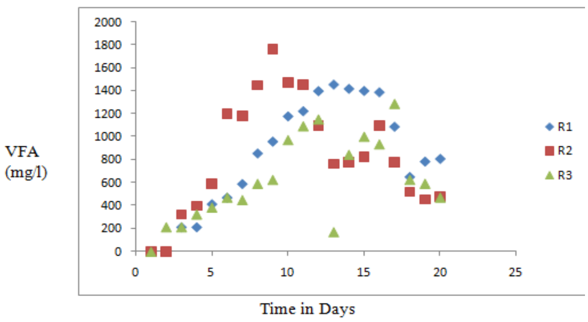

Figure 3: Variation in VFA Generation

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International Journal of Advanced Research in Science, Engineering and Technology
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C.VARIATION IN COD

Kitchen waste contains high organic matter. Initially the COD obtained was less in concentration, but as the time increased the concentration of COD was also increased up to 365000 mg/l in the Reactor 2. The COD of the leachates obtained was highest in the span of 12-15 days. It is because the degradation of organic matter is more in that period. [9] After 8th day, COD started decreasing, because organic content of mixture in the reactor was reducing. pH was found to be between 4-6. More soluble monomers are converted to small molecules and thus results the phenomenon that VFAs production kept on increasing but COD was decreasing [12]. The amount of COD in the leachate decreased, which might result from the microbial utilization of soluble substrates in the leachate [13]. COD variation is shown in figure 4.

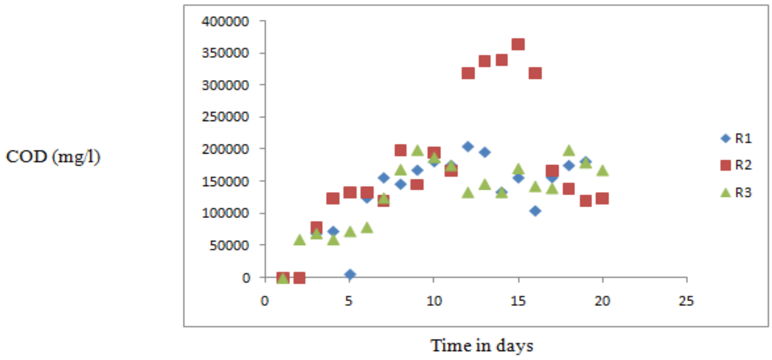

Figure 4: Variation in COD

D.PROCESS KINETICS OF HYDROLYSIS AND ACIDIFICATION OF KITCHEN WASTE

In process kinetics study of kitchen waste, during hydrolysis and acidification, digestion time is important factor for the performance of a hydrolysis-acidification reactor, since it determine the solid solubilisation efficiency and degree of acidification. For the previous study a HRT of 10 days was found to be optimum. Eastman and Ferguson (1981) successfully used first-order kinetics for the description of solids reduction in a single-stage steady-state anaerobic digester. Hydrolysis, being the first step in overall process, is normally the rate-limiting step of the overall anaerobic digestion process, if the substrate is in solid form. Large size particles with a low surface-to-volume ratio are hydrolysed more slowly than small particles [14]. Hydrolysis of complex polymeric substances constitutes the rate-limiting step [15]. Biodegradability of bio-waste components ranged from 5% to 90% without dependence on temperature. Acidification is also influenced by the temperature in accordance with Arrehenius Law, but there is no agreement about the selection of temperature.

D.1. ACIDIFICATION EFFICIENCY

Acidification efficiency was found increasing with increase in time. Initially the acidification efficiency was 16.42%. On 3rd day and reached upto 62% on the 9th day. It indicates that degradation of solids in the reactor was slow initially increases at later stage. The acidification efficiency of the reactor can also be expressed as a function of the VFA concentration present in the influent and effluent as under. The acidification efficiency was found to increase from 16.42% to 62.00% in the initial four days of digestion time after which it remains more or less constant.

D.2. HYDROLYSIS YIELD

The primary products of hydrolysis process are soluble monomers which can be measured as soluble COD [12]. The hydrolysis yield and the rate were decreasing with respect to time. Hydrolysis yield was 58% at pH 7 during hydrolysis of kitchen waste on 10th day. At day 3 hydrolysis yield was 10.23% which was increased to 63.2%. The hydrolysis yield was decreasing after 6 days. After that it went on decreasing. In literature, the undissociated organic acids were regarded inhibitive to microorganisms because undissociated acid could pass through cell membranes more easily than dissociated form.

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E. STUDIES ON BIO-ENERGY HARVESTING USING MICROBIAL FUEL CELL (MFC)

E.1. STARTUP

During the start-up period, the anode compartment was fed with 600 ml of influent comprising of leachate and inoculums and kept idle for 10 days for development of anaerobic condition. The anode chamber was fed with influent with a low COD concentration of 500 mg/l. MFC was then operated for next 11 days and current and voltage were observed daily during this period. Fully anaerobic condition, pH between 6-7 and operated at room temperature. Resistance of 100Ω was maintained constant. Initially the current and voltage obtained at this stage was too small and it increases with time, it happened because of insufficient contact time between microorganism and substrate. At end of acclimatization period, the current observed was 4μA and voltage is 33 mV.

E.2. SUBSTRATE DEGRADATION

The COD reduction at varying hydraulic and organic loading was measured. Hydraulic retention times used were 48, 36, 24, 16, 12 hours. Reduction of COD was less at lower HRT; it increases to highest at HRT of 24 hours and further reduces at higher HRT. Operating pH and applied substrate loading rate showed marked influence on the substrate degradation efficiency [16]. It was noticed that 24 hours HRT is suitable for highest removal of COD. It provides good reaction time for reduction of organic matter. As the flow rate increased the HRT decreased in the anode chamber. The time required by the microorganisms in the anodic chamber to degrade organic matter decreased with increased flow rate. Therefore, the average COD removal efficiency of each culture decrease [17].The results indicated that HRT is an important parameter affecting on electrical performance of a MFC working at continuous mode.

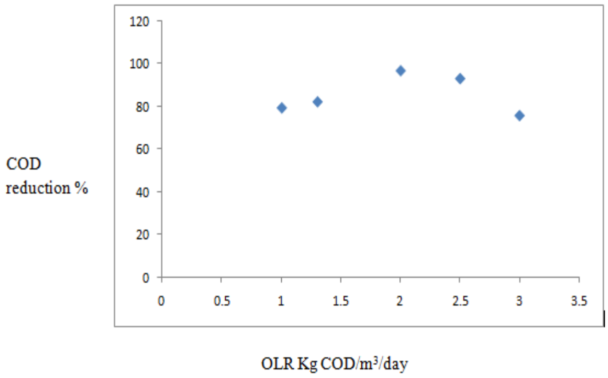

Figure 5: Variation in COD reduction with HRT

The performance of fuel cell depends on the substrate loading rate. COD reduction also studied by observing different OLR. Its variation is shown in Fig. 3.5.2. Four different OLRs i.e. 1.0, 1.3, 2.0, 2.5 and 3.0 kg COD/m^3/day selected for this study. It was observed that at initial OLR1, 1.0 Kg COD/m^3/day reduction in COD found was 79.53%. After, further increase in OLR, COD reduction was also increased up to 96.69% at the OLR3, 2.0 Kg COD/m^3/day. The increment in substrate loading has showed a positive influence on the COD reduction [18]. Figure 5 shows the influence of HRTs on COD reduction. This might be due to the higher substrate availability at OLR3 compared to OLR2 and OLR1. Further increase in organic loading marked drop in MFC performance and thus the study was stopped at this juncture. At OLR3 better substrate reduction with higher bio-energy and thus considered as the optimum loading condition of MFC with Kitchen waste as anodic fuel.

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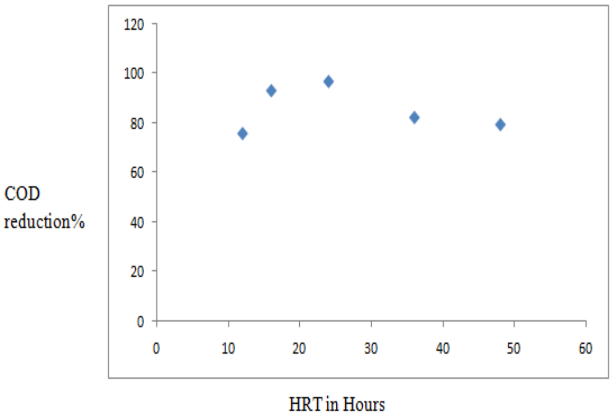

Figure 6: Influence of HRTs on COD reduction

F. BIO-ELECTRICITY GENERATION

F.1. MEASUREMENT OF CURRENT AND CELL POTENTIAL

The variation in current and voltage is shown in figure 7 and figure 8. The current and voltage increased with increase in OLR. This was because of increased OLR has more organic matter due to which microbes can get enough substrate for anaerobic digestion which was responsible for more protons release to generate more current and voltage. The highest current and voltage was observed during 65-80 days when the organic loading was 2.5 kg COD/m^3/d and at HRT of 16 hours. Maximum current obtained was 68 µA and voltage 889 mV. Maximum current and voltage were obtained with maximum power density. A higher current leads to a higher migration of ions to balance the charge [19]. The rate of electron flow through the circuit was limited by different types of resistances such as the external resistor, electron transfer between solution and electrode surface and mass transfer in solution [20].

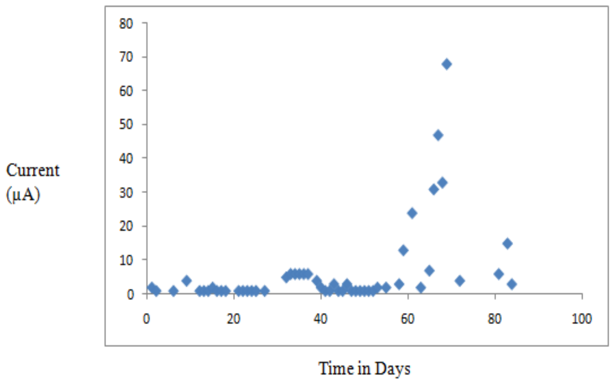

Figure 7: Variations in Current

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International Journal of Advanced Research in Science, Engineering and Technology
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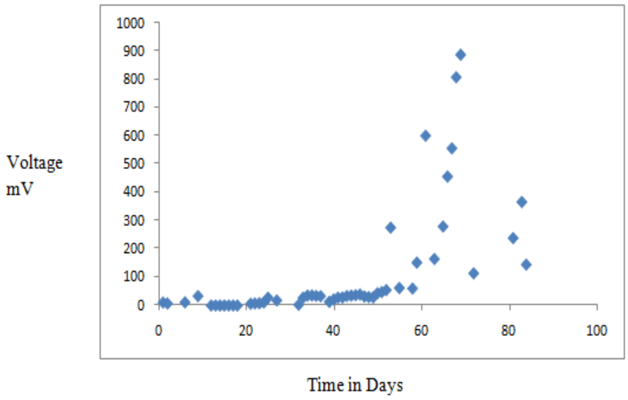

Figure 8: Variation in Voltage

F.2. POWER DENSITY

When leachate was being added to the MFC, the current or power density increased. Maximum current density and power density were in the duration of 60-80 days and it was 0.346 mA/m^2 and 308.42 mW/m^2. At the same stage maximum current and voltage was also observed. Initially current and voltage were less it was because of less OLR. Once OLR increased current and voltage were also increased. The voltage increased and then stabilized according to the suspected principle of electricity generation [21]. The relation current density and power density is depicted in figure 9. All the MFCs showed increased power densities as the current density increased until the power densities decreased sharply. This phenomenon is common for all MFCs when the power density based on the current density is compared [22]. The order of the voltage is the same as the power density.

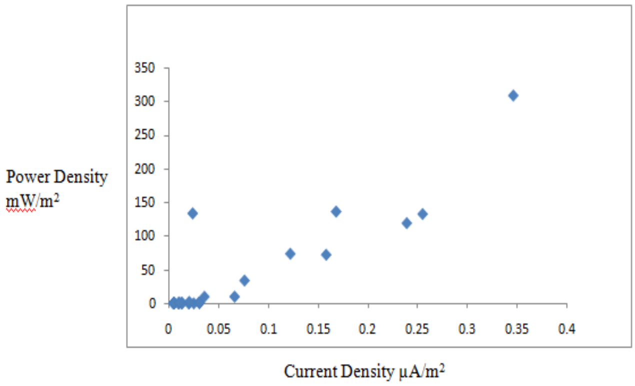

Figure 9: Relation between Current Density and Power Density

V. SUMMARY AND CONCLUSION

In co-digestion study of Kitchen waste, vegetable waste and saw dust optimized proportion of 20:20:60 was found to be optimum using Leachate Bed Reactor. The composition of kitchen waste always varies due to issues such as seasonal dietary habits. Maximum volume of leachate was obtained in the duration of 10-12 days. LBR produced highest VFA concentration of 1762 mg/l in the duration of 7-9 days. pH maintained was 4-6. Highest acidification efficiency observed was 62%. It indicates that using LBR acidification efficiency can be increased. Hydrolysis yield obtained was 63.2 % in 5-6 days duration. Hydrolysis yield shows the degradation of organic matter.

During harvesting of electricity using kitchen waste as substrate, the effects of operational conditions of a microbial fuel cell were tested and optimized for the best performance of a mediator-less microbial fuel cell. After providing the start-up time of 11 days, there was small increment in current 4 µA and voltage 33mV. The COD removal efficiency

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
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over 96.69% was obtained; amongst all five OLRs at the OLR3 2.0 Kg COD/m^3/day this proves the effectiveness of such MFC configuration for kitchen waste treatment. Highest current was achieved up to 68µA and voltage up to 889mV. Maximum current and voltage occurred at the OLR 2.5 Kg COD/m^3/day with HRT 16 hours. Current density obtained was 0.346 mA/m^2, which was too small. As the conductor area was small more current could not be achieve. The power generation was found to be higher at intermittent organic load during experiment, at the duration of 60-80 days. Power density obtained was 308.42 mW/m^3. Better performance of such low cost MFC, can take this technology a step ahead towards commercialization.

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