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# Greywater Treatment with Simultaneous Generation of Energy Using Low-Cost Microbial Fuel Cells

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Microbial fuel cells (MFCs) are an emerging type of biological wastewater treatment units with simultaneous power generation. The present study demonstrates an effective treatment of greywater and generation of electricity in a double-chambered MFC. This MFC was fabricated using cost-effective and easily available materials replacing expensive materials like Nafion membranes, graphite electrodes, etc. Experimental results showed a maximum open circuit voltage of $0.64 \pm 0.04$ V and $114 \pm 1.41$ mA current during the study period. The results further indicate a maximum power generation of 24.50 mW along with 307.69 mW/m² of power density; 34.62 mA/m² of current density, 1.33 W/m³ of volumetric power density, 0.15 A/m³ of volumetric current density and a power yield of 0.40 mW/kg of COD removal. The chemical oxygen demand (COD) removal efficiency was 77.6%. The use of low-cost and easily available raw materials has brought down the total manufacturing cost of MFCs used in this study to less than USD 4.0. However, the performance of the MFCs used in the current study is comparable with other sophisticated MFCs built with expensive raw materials, as reported in the literature. This cost-effective MFC used in the present study might be an effective replacement of expensive MFCs for wastewater treatment at scaled-up levels.

Keywords: *greywater, microbial fuel cell (MFC), wastewater treatment, cost-effective, power output.*

## 1 Introduction

A huge volume of wastewater is being discharged annually from domestic, industrial and agriculture sectors. Greywater is the wastewater exiting from households; excluding the wastewater from toilets and including bathrooms, bathtubs, showers, hand wash basins, laundry machines and kitchen sinks. In order to manage the alarming threat of drinking water scarcity in and around the world, there is an increasing demand in the treatment and reuse of greywater. About 75% of residential sewage fraction is greywater (Eriksson *et al.*, 2002). As compared with black (toilet) water, greywater contains low concentrations of organic compounds, nutrients and pathogens (Otterpohl, 2002). Therefore, in order to manage the water scarceness, it makes sense to collect greywater separately and treat it for irrigation, washing or other non-potable applications. It should be treated properly to meet the discharge standards prior to their release into the environment (Suzuki *et al.*; 2002, Maekawa*et al.*, 1995).

Many treatment techniques have been proposed for the removal of inorganic and organic pollutants from wastewater. Most of these processes entail high operational costs or large areas of land for treatment (Min *et al.*, 2005). In this scenario, high energy requirements of conventional sewage treatment systems demand an alternative treatment technology, which will be cost-effective and require no or less energy. Anaerobic technologies have been finding increasing application in the past few decades in the treatment of domestic and industrial wastewater with dual benefit of wastewater treatment as well as energy production in terms of methane-rich biogas. Process instability and microbial flush-out are the main drawbacks of anaerobic reactors, particularly in a small-scale biogas plant (Gangrekar & Shinde, 2006). An alternative technique emerging more recently for wastewater treatment and energy production is microbial fuel cells (MFCs). In MFCs, electricity can be produced with simultaneous degradation of organic matter by microorganisms. MFCs are generally fabricated into 2 chambers: one is anode chamber, while the other is cathode chamber. The cathode chamber is maintained with anaerobic conditions and the organic material given as a substrate will be oxidised by the anaerobic microorganisms; the electrons lost in the process are transferred to the anode by either an electron carrier (mediator) added in the MFC or directly from the respiratory enzyme of the microbes (mediator less) (Logan *et al.*, 2007)

From the literature survey, it can be noted that extensive research on microbial fuel cells is going on on a laboratory scale and most of such studies have been using double or single chamber MFCs with expensive raw materials including Nafion-based proton exchange membranes (Logan *et al.*, 2007; Venkata Mohan *et al.*, 2008; Greenman *et al.*, 2009; Wen *et al.*, 2009; Sangeetha *et al.*, 2011). The generation of electricity using MFCs with different substrates has also been reported. In most of the MFCs, pure compounds such as acetate (Bond & Lovely, 2003), glucose (Rabaey *et al.*, 2003), sucrose (He *et al.*, 2006), amino acid (cysteine; Logan *et al.*, 2005), and proteins (bovine serum albumin) (Heilmann & Logan, 2006) are used as substrates. Wastewater from various industries, such as swine (Min *et al.*, 2005), meat packing (Heilmann & Logan, 2006), food processing (Kim *et al.*, 2004), beer brewery, paper (Mathuriya & Sharma, 2009a, 2009b), corn stover hydrolysates (liquefied corn stover) (Zuo *et al.*, 2006), food processing industries (Sangeetha *et al.*, 2011), and wastewater from domestic activities (Liu *et al.*, 2004) have also been treated using MFCs. Most of the previous studies have reported that MFCs operated with wastewater generate a lower amount of energy than those operated with pure compounds.

Greywater, even though it is a good source of organic matter, has not been reported so far as a substrate in MFCs. Hence, in the present study, greywater was used as a substrate in double-chambered MFCs. Double-chambered MFCs have been successfully operated by many researchers for the simultaneous generation of electricity and wastewater treatment (Min *et al.*, 2005; Raghavulu *et al.*, 2009; Jadhav & Ghangrekar, 2009; Sangeetha *et al.*, 2011) with expensive raw materials, such as graphite electrodes and Nafion-based proton exchange membranes. Hence, the development of MFCs with cost-effective raw materials is a thrust area of research in MFC studies. In this context, the major objective of the present study is to develop laboratory-scale MFCs with cost-effective materials and use them in greywater treatment. The performance of double-chambered MFCs treating greywater was assessed in terms of electricity production, removal of chemical oxygen demand (COD removal) and total solids (TS).

## 2 Materials and methods

### *2.1 Substrates used*

Greywater was collected from the student's hostel of Mahatma Gandhi University and stored under the refrigeration at 4°C before use. After analysing the characteristics (Table 1), greywater was used as the substrate for MFC without any modifications, such as pH adjustment or the addition of nutrients/trace metals. The experiments were conducted using full-strength wastewater.

### *2.2 Microbial fuel cells*

The whole experiment was designed with 2 double-chambered MFCs, which were fabricated with salt bridges as described by Mohan *et al.*, (2008) and Min *et al.*, (2005). Two polyethylene terephthalate (PET) bottles of 400 mL capacity were used as 2 chambers of each MFC. One bottle was used as the anode chamber and maintained under anaerobic conditions. The other bottle was used as the cathode chamber, maintained aerobic by providing an external air supply with a sparger network (Mohan *et al.*, 2007). Carbon brushes were used as electrodes in each chamber. The electrodes were kept 10 cm apart from each other and were externally connected through copper wires after sealing the contact area with epoxy resin. The chambers were provided with inlet and outlet ports. Both the anode and cathode chambers were connected through a salt bridge of 8.5 cm length and 1.1 cm inner diameter, prepared by using KCl solution and agar-agar.

### *2.3 Experimental methods. MFC operation*

MFC operation was started by filling the anode chamber with 250 mL of greywater (substrate) and 50 mL of digested effluent from an ongoing anaerobic reactor as inocula. In all MFCs, the cathode chamber was kept in aerobic conditions with KCl solution (300 mL) as catholyte and was replenished once in a week as it got denatured. Initially, the MFCs were operated in the batch mode for 10 days, i.e. without further addition of the substrate during this period. This is to facilitate the acclimatisation of microbes with the substrate. After 10 days of the batch mode, both MFCs were operated semi-continuously for a total period of 30 days with 6 cycles of feeding at an interval of 5 days each. On each cycle, daily feeding of 50 mL of the substrate was carried out and, thus, at the end of each cycle, a total of 250 mL substrate was treated. The total experimental period including the batch mode of operation was 40 days. Daily monitoring of voltage and current was carried out during the study period, with different loads of resistance using a digital multimeter. Periodic assessment of greywater treatment in MFCs was done in terms of COD and total solids removal.

Total (dry) solids, volatile solids and chemical oxygen demand (COD) of the influent and the effluent of the MFCs were determined as per standard methods of APHA (1995). Power (W) was calculated using the relation $P = v^2/R_{external}$, where v represent voltage (V) and R is the external resistance load. Power density ($mW/m^2$) and current density ($mA/m^2$) were calculated by dividing the obtained power and current by the anode surface area ($m^2$). Power yield (W/kg COD removal) was obtained by dividing power with corresponding substrate (COD) removal values. Volumetric power ($W/m^3$) and current density ($A/m^3$) were calculated based on the anode liquid volume (Venkata Mohan *et al.*, 2007).

## 3 Results and discussion

The characteristics of greywater used in the study was analysed and the results are presented in Table 1. Daily monitoring of voltage and current was carried out during the study period, with different loads of resistance using a digital multimeter. Each measurement lasted for 3 minutes at each resistance and concordant values. The results were presented as average of MFCs calculated to evaluate the performance of respective duplicate cells of MFCs.

*Table 1. Characteristics of greywater used as substrate in MFC.*

| Parameters | Characteristics | | | | | |
|---|---|---|---|---|---|---|
| | *1st cycle* | *2nd cycle* | *3rd cycle* | *4th cycle* | *5th cycle* | *6th cycle* |
| pH | 6.30 | 6.52 | 6.45 | 6.25 | 6.20 | 6.14 |
| Total Solids (mg/L) | 1,915 | 1,910 | 2,440 | 2,555 | 2,030 | 1,900 |
| Nitrate (mg/L) | 6.50 | 6.81 | 7.13 | 7.77 | 7.43 | 7.89 |
| Sulphate (mg/L) | 15.85 | 15.67 | 16.47 | 15.69 | 15.15 | 16.33 |
| Phosphate (mg/L) | 22.69 | 23.71 | 24.25 | 24.16 | 22.80 | 23.69 |
| Chemical Oxygen Demand (mg/L) | 1,382 | 1,396 | 1,402 | 1,402 | 1,384 | 1,400 |

*Results in terms of electricity generation from wastewater*

After inoculation and feeding, a slow increase in the current was observed in all MFCs. After 10 days of acclimatisation of the microbes with the substrate, a steady current was observed as output in MFCs. The development of microbial population in the form of biofilm has been found to occur between 6 to 15 days until a stable current generation was obtained (Liu *et al.*, 2005). In the present study, the open circuit voltage (OCV) was also observed as a steady output after 10 days of operation. OCV is the cell voltage between 2 terminals of a device when disconnected from any circuit. The maximum OCV of 0.64 ± 0.04 V and 114 ± 1.4 mA of the current were recorded on day 36 (Figure 1). From the figure, it is clear that the potential of the MFC increases as the number of days increases. The results obtained in the present study are comparable with those of Dalvi *et al.* (2011), who conducted a study on electricity generation with paneer whey degradation with different microorganisms in a dual-chambered MFC and the results showed an OCV of 0.45 V.

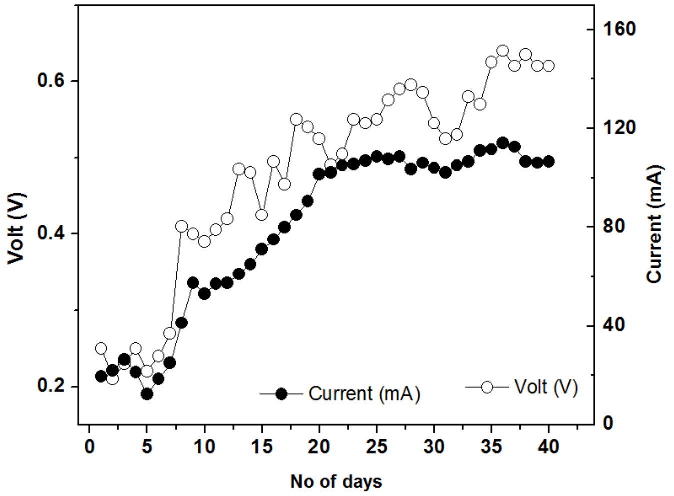


*Figure 1. Open circuit voltage and current of MFC treating greywater.*

Even though the performance of an MFC can be evaluated in many ways, it is principally done with power output. The power output is usually normalised to the projected anode surface area, where most of the biological activity occurs. In the present study, the power production in MFCs reached the maximum of 24.50 mW on day 36 (Figure 2). It may be noted that the power output showed increments after each feeding of MFCs, indicating multiplication of microbes and their acclimatisation to the new microenvironment. A gradual rise in power was observed after every fresh feed addition, which indicates that the attached microbes on the anode as biofilm contributed to the electricity generation rather than the suspended ones. Sangeetha & Muthukumar (2012) in their study on using sago wastewater have reported 8.1 mW power using graphite as electrode on day 17 of the experiment. Their results also supported the view that the power output showed increments after each feeding.

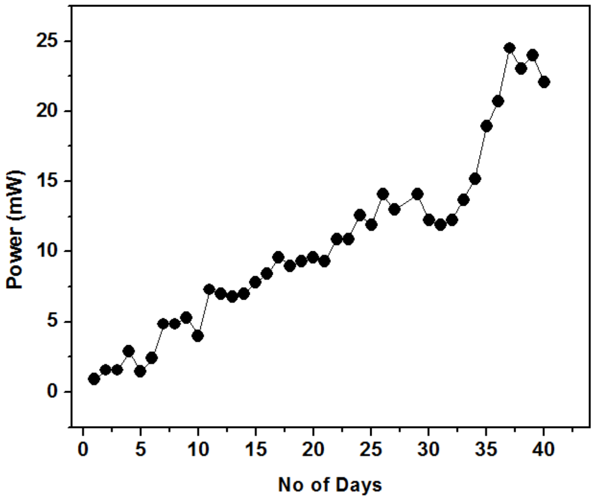


*Figure 2. Power generation graph of MFC treating greywater.*

Table 2 shows the power generation details of MFCs. At the continuous external load of 100 Ω resistances, the maximum power density of 307.69 mW/m$^2$, current density of 34.62 mA/m$^2$, volumetric power density of 1.33 W/m$^3$, and volumetric current density of 0.15 A/m$^3$ were recorded.

*Table 2. Average power generation details of MFCs at 100 Ω resistances.*

| No of Days | Power density mW/m$^2$ | Volumetric power density W/m$^3$ | Current density mA/m$^2$ | Volumetric current density A/m$^3$ |
|---|---|---|---|---|
| **1-10 days*** | **0.275 ± 0.123** | **0.001 ± 0.001** | **1.231 ± 0.649** | **0.005 ± 0.003** |
| 11 | 0.62 | 0.0027 | 3.0769 | 0.0133 |
| 12 | 0.77 | 0.0033 | 3.8462 | 0.0167 |
| 13 | 0.77 | 0.0033 | 3.8462 | 0.0167 |
| 14 | 3.08 | 0.0133 | 4.6154 | 0.0200 |
| 15 | 4.81 | 0.0208 | 6.1538 | 0.0267 |
| 16 | 6.92 | 0.0300 | 6.9231 | 0.0300 |
| 17 | 12.31 | 0.0533 | 6.1538 | 0.0267 |
| 18 | 19.23 | 0.0833 | 7.6923 | 0.0333 |
| 19 | 43.27 | 0.1875 | 7.6923 | 0.0333 |
| 20 | 23.27 | 0.1008 | 15.38462 | 0.0667 |
| 21 | 27.69 | 0.1200 | 15.38462 | 0.0667 |
| 22 | 43.27 | 0.1875 | 21.53846 | 0.0933 |
| 23 | 43.27 | 0.1875 | 22.30769 | 0.0967 |
| 24 | 37.69 | 0.1633 | 14.61538 | 0.0633 |
| 25 | 49.23 | 0.2133 | 34.61538 | 0.1500 |
| 26 | 49.23 | 0.2133 | 22.30769 | 0.0967 |
| 27 | 43.27 | 0.1875 | 27.69231 | 0.1200 |
| 28 | 49.23 | 0.2133 | 22.30769 | 0.0967 |
| 29 | 55.58 | 0.2408 | 29.23077 | 0.1267 |
| 30 | 55.58 | 0.2408 | 20.76923 | 0.0900 |
| 31 | 49.23 | 0.2133 | 15.38462 | 0.0667 |
| 32 | 49.23 | 0.2133 | 15.38462 | 0.0667 |
| 33 | 62.31 | 0.2700 | 21.53846 | 0.0933 |
| 34 | 76.92 | 0.3333 | 22.30769 | 0.0967 |
| 35 | 69.42 | 0.3008 | 14.61538 | 0.0633 |
| 36 | 173.08 | 0.7500 | 34.61538 | 0.1500 |
| 37 | 173.08 | 0.7500 | 22.30769 | 0.0967 |
| 38 | 307.69 | 1.3333 | 27.69231 | 0.1200 |
| 39 | 235.58 | 1.0208 | 29.23077 | 0.1267 |
| 40 | 76.92 | 0.3333 | 20.76923 | 0.0900 |

**1-10 days – the batch mode of operation was carried out, and the average values of the results are presented.*

Lu *et al.* (2009) operated an MFC with starch processing wastewater containing 4,900 mg/L of COD over 4 cycles and obtained the maximum power density of 239.4 mW/m$^2$ in the third cycle. Similar results were also reported by Sangeetha *et al.*, (2011) with food processing wastewater. The distance between cathode and anode plays an important role in power generation of fuel cells. As the distance between the 2 electrodes is less, the resulting power output will be high by dropping the ohmic resistance

(Jang *et al.*, 2004). In the present study, the electrodes of MFCs were kept at a distance of 10 cm resulting in good power output (Figure 2). The effect of electrode distance on MFC performance was carried out by Sangeetha & Muthukumar (2012) varying it as 10 cm, 12 cm and 15 cm. Their study revealed that electrode distance of 10 cm resulted in increased power production with a voltage of 900 mV (millivolts), current of 9.0 mA (milliamps) at 100 Ω resistances and COD removal of 94%. A similar trend of an increase in MFC performance with a decreasing distance between the electrodes was observed by Liu *et al.* (2005), Kim *et al.* (2007), Ghangrekar & Shinde (2007), and Cheng *et al.* (2006).

*Effect of organic loading rate on power generation.*

The amount of electricity produced from wastewater depends upon COD loading (Oh and Logan, 2005). The present study showed greater power output with high COD loading. Wastewater from various sources with a COD ranging 1,000 – 10,000 mg/L is a potential substrate for MFCs (Pant *et al.*, 2009). Greywater used in the present study had an average COD value of 1394.33 ± 9.04 mg/L. The overall COD removal efficiency observed in the present study was 71.36 ± 1.93%, demonstrating the feasibility of this configuration of MFCs as an effective wastewater treatment system, also ensuring better effluent quality. The organic matter present in greywater at the anode chamber was effectively consumed by microorganisms resulting in COD removal from greywater (Figure 3). Power yield of MFCs with respect to daily COD removal was calculated and shown in Figure 4. In accordance with the COD reduction results, MFCs showed a power yield of 0.40 mW/kg COD removal.

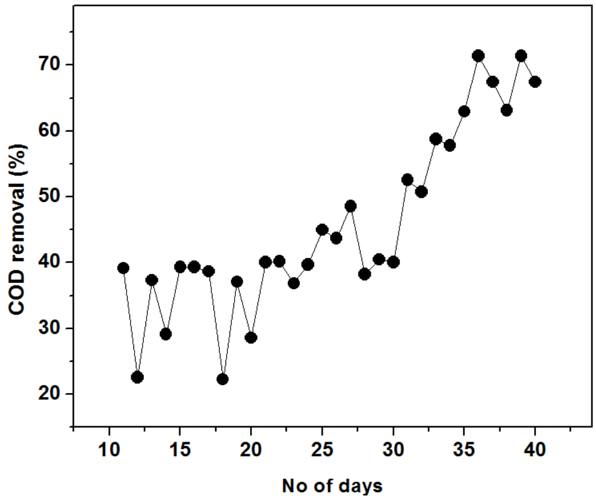


*Figure 3. Results in terms of percentage COD removal.*

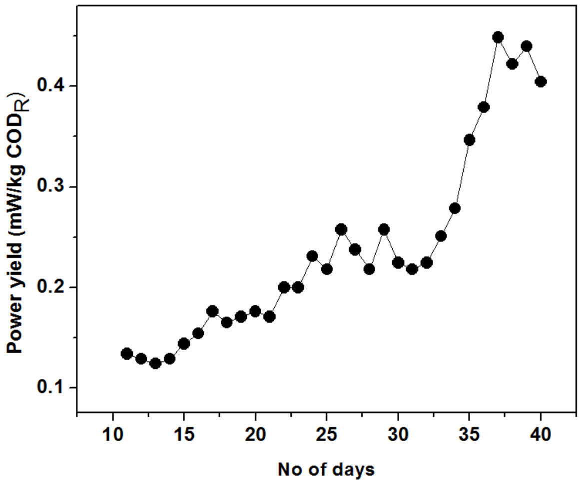


*Figure 4. Power yield of MFC treating greywater.*

The solid removal efficiency of MFCs was also analysed and the results are shown in Figure 5. During the study period, the effluent samples from both MFCs showed a gradual decrease in the concentration of total and volatile solids due to the microbial action.

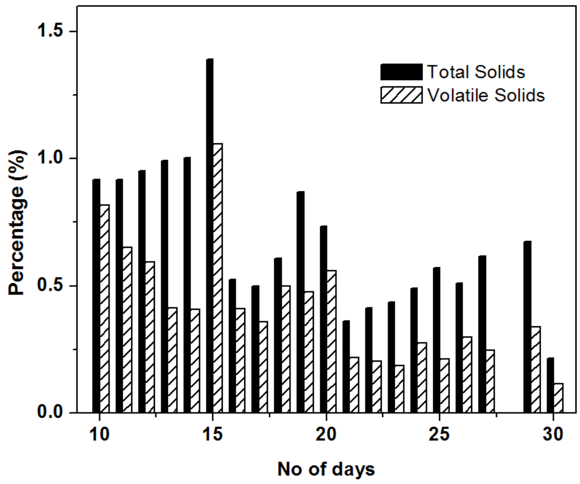


*Figure 5. Total and volatile solid concentration in the effluent from MFCs.*

## 4 Conclusions

The efficiency of MFCs used for the treatment of greywater was successfully evaluated in the present study with remarkable results of electricity production and COD removals. One of the major drawbacks of conventional MFCs, which utilize graphite electrodes and Nafion-based proton exchange membranes, is high cost. The significance of the present study is the cost effectiveness of the raw materials used for the fabrication of MFCs. In the present study, in order to transfer protons to the cathode, a salt bridge and carbon brushes were used as electrodes, which are less expensive and easily available. This low-cost MFC, with the manufacturing cost of less than USD 4.0, has performed with comparable performance on a par with many sophisticated MFCs employing expensive proton exchange membranes. The low-cost MFCs used in the present study may be an effective alternative for an expensive Nafion-based MFC in wastewater treatment at scaled-up levels. However, the lower electrode potential of the present MFC has to be improved by decreasing its internal resistance. Further studies are presently going on towards improving the performance of the cathode with less internal resistance using low-cost raw materials.


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# Pilkojo vandens valymas ir elektros energijos generavimas, naudojant nebrangius mikrobinius kuro elementus

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(gauta 2015 m. liepos mėn.; priimta spaudai 2015 m. rugsėjo mėn.)

Mikrobiniai kuro elementai (angl. microbial fuel cells – MFCs) – tai besivystantys biologinio nuotekų tvarkymo technologija, kuri tuo pačiu metu generuoja elektros energiją. Šis tyrimas pristato efektyvų pilkojo vandens valymą kartu su elektros energijos gamyba dvigubos kameros MFCs. MFCs buvo pagaminti naudojant rentabilias ir lengvai prieinamas medžiagas, pakeičiant tokius brangius metalus, kaip Nafion membranos, grafito elektrodai ir pan. Eksperimentiniai rezultatai parodė, kad tyrimo metu didžiausia atviros elektros srovės įtampa siekė 0,64 ± 0,04 V, o srovės stipris 114 ± 1,41 mA. Rezultatai taip pat parodė, kad išvystyta galia siekė 24,5 mW, kai galios tankis buvo 307,69 mW/m²; srovės stiprio tankis 34,62 mA/m², galios tūrinis tankis 1,33 W/m³, srovės stiprio tūrinis tankis 0.15 A/m³ ir galios išeiga 0,40 mW/kg cheminio deguonies suvartojimo (ChDS) panaikinimui. ChDS pašalinimo efektyvumas siekė 77,6%. Nebrangių ir lengvai prieinamų žaliavų naudojimas leido sumažinti šiame tyrime naudotų MFCs bendrus gamybos kaštus iki mažiau nei 4,0 JAV dolerių. Nepaistant to, šiame tyrime naudotų MFCs rezultatai gali būti sulyginami su kitais sudėtingais MFCs, kurie yra sukurti naudojant brangias žaliavas, pateiktas literatūroje. Šie rentabilūs tyrime naudojami MFCs gali būti efektyvus pakaitalas brangiems MFCs, kurie naudojami nuotekoms valyti aukštesniuose lygiuose.

Raktiniai žodžiai: *pilkasis vanduo, mikrobinis kuro elementas, nuotekų valymas, rentabili galios išeiga*.