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Electricity generation during sauerkraut fermentation process

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The possibility of using sauerkraut juice as an anolyte in a microbial fuel cell (MFC) was previously proved by us. In this study, fifty day-long MFC experiments covering the total term of the sauerkraut fermentation process were performed. A change in the electrochemical behavior of sauerkraut juice, associated with the successive loading of different dominating microbial species in the mixed microflora, as well as accumulation of various intermediate and end metabolites, was observed by means of cyclic voltammetry. The highest MFC power density of 1.87 W/m^3 was achieved by using a fresh sauerkraut juice as an anolyte at the early stage of fermentation, when hetero-fermentative species are developed into the medium. However, the maximum power density of a MFC permanently loaded with external resistance was obtained after a month operation, corresponding to the lower development of hetero-fermentative lactic acid bacteria and their substitution with homo-fermentative bacteria. Stable long-term current density of 1.05±0.10 A/m^3 was generated at the later fermentation stages.

Keywords: microbial fuel cell, sauerkraut fermentation, electricity generation

INTRODUCTION

The great idea of the microbial fuel cell (MFC) concept is connected with electricity generation based on the naturally occurring metabolic processes of microorganisms. Thus, the MFC technology is expected to have an impact on both electricity production from renewable sources and biodegradable waste purification [1–4].

Food industry is one of the biggest sources of waste biomass. Different methods for its minimization or re-utilization, depending on the specific origin and technology, are in use [5, 6].

Recently, MFC technology has been proposed as an alternative of some of these technologies [7, 8], however, a lot of research has to be done for its practical implementation.

The sauerkraut production, based on lactic acid fermentation of cabbage, is wide-spread in many countries. In our recent study, the possibility to use sauerkraut juice as an anolyte in MFC was proved [9].

The aim of the present work was to verify the possibility for continuous electricity generation by MFC based on sauerkraut fermentation. For this purpose, long-term experiments covering the total period of the sauerkraut fermentation process were performed.

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EXPERIMENTAL

Cabbage fermentation was undertaken in a 5 l fermentor, placed into a thermostat-incubator at 16 °C. 4% NaCl soultion was used as a brine.

The electrochemical behavior of the produced sauerkraut juice in the progress of the fermentation process was examined by means of cyclic voltammetry (CV). A sample of the juice was taken from the fermentor and placed into a three-electrode electrochemical cell. Platinum ORP electrode was used as a working electrode, platinum mesh as a counter electrode and Ag/AgCl as a reference. The potential was swept with a scan rate of 25 mV/s. The CV measurements were performed on a 35-2 PJT potentiostat-galvanostat (Radiometer-Tacussel, France) with IMT-101 electrochemical interface and VoltaMaster2 software.

Sauerkraut juice (100 ml) along with cut pieces of cabbage leaves as a carbohydrate source were introduced in the anodic compartments of two identical double-chamber MFCs. Buffered solution (pH 7) of 0.1 M $K_3[Fe(CN)_6]$ was placed in the cathodic chambers and served as a catholyte. The anodic and cathodic compartments were connected with a salt bridge. Rectangular shaped pieces of carbon felt (SPC–7011, 30 g/m^2, Weißgerber GmbH & Co. KG) with geometric area of 21 cm^2 were used as both anodes and cathodes. The inoculated MFCs were kept in a thermostat-incubator at 16 °C along the whole experiment duration. One of them (MFC 1) was kept at open circuit and once per day polarization measurements by stepwise change of the external resistance from 10 kΩ to 0 Ω were carried out. The second microbial fuel cell (MFC 2) was permanently polarized by switching a load resistance (1 kΩ) in the external circuit and its terminal voltage was monitored by a digital multimeter (Lamar RE67). From the obtained data, the generated current was estimated by using Ohm's law. Periodically, polarization measurements by varying the external resistance were accomplished.

As a control experiment, cabbage juice was periodically taken from the fermentor, introduced into a third MFC and after stabilization of the open curcuit voltage (OCV), polarization measurements at variable resistances were performed.

RESULTS AND DISCUSSION

The CV-measurements performed with the sauerkraut juice reveal that a broad anodic peak with varying intensity and potential appears in the voltamograms. At the first days of the fermentation process the peak intensity grew and its potential shifted from –380 to –270 mV (*vs*. Ag/AgCl) – Fig.1a. Till the 10^{th} day the CV-pattern remained unchanged, but with the progress of the fermentation process the anodic peak shifted to more positive potentials and its height was reduced – Fig.1b.

The recorded variable electrochemical behaviour could be associated with the successive loading of different dominating microbial species in the mixed microflora, as well as with oxidation of various intermediate and end metabolites produced during fermentation. The sauerkraut production is based on lactic acid fermentation. The starter for sauerkraut is the normal mixed biota of cabbage, in which the main species are *Leuconostoc mesenteroides* and *Lactobacillus plantarum*. The addition of 2.25–2.50 % salt restricts the activities of gram-negative bacteria, while the lactic acid rods and cocci are favored. The activities of the cocci usually cease when the acid content increases to 0.7–1.0 %. The final stages of sauerkraut production are effected by *L. plantarum* and *L. brevis*. *P. cerevisiae* and *E. faecalis* may also contribute to product development. The final total acidity is generally 1.6–1.8 %, with lactic acid at 1.0–1.3 % and pH in the range of 3.1 to 3.7 [10]. The depletion of the main substrates at the end of the process is the most probable reason for the observed decrease of the anodic peak intensity in the CVs.

The MFC experiments using sauerkraut juice as an anolyte confirmed the possibility for electricity generation along the sauerkraut fermentation process – Fig.2. The obtained data show that the system is rapidly adaptive and starts to produce electricity immediately after innoculation of the MFC.

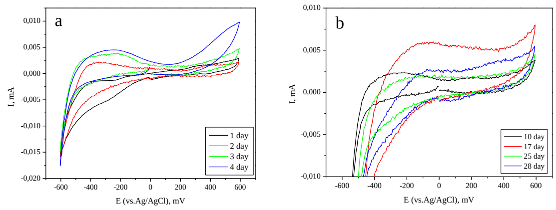

Fig. 1. Cyclic voltammograms obtained with sauerkraut juice at different stages of fermentation.

When not loaded with an external resistance (MFC 1), the OCV initially increased from 470 to 750 mV and held at close values for two weeks (Fig.2a). After this period it sharply dropped back to 500 mV and then gradually grew up to a stationary value of 580±15 mV. Analogous tendencies in the change of the maximum power density, estimated from the obtained polarization curves, were observed. The highest value of 745 mW/m^3 was achieved at the 4^{th} day after MFC innoculation. After two weeks the generated power drastically dropped to 220 mW/m^3, but afterwords it gradually increased to 300±25 mW/m^3. At the end of the experiment both OCV and maximum power values fell down.

Complex variation of OCV and maximum power density was also observed when a load resistance was permanently switched on in the external current circuit (MFC 2, Fig.2b). The obtained lower values could be assigned to the fact that the system was enduringly under "stress" caused by the continuous electricity production. This is especially valid for the initial period, when a significant decrease of the maximum power was observed. During the next stage, however, the variation of both OCV and maximum power values is similar to that achieved with MFC 1.

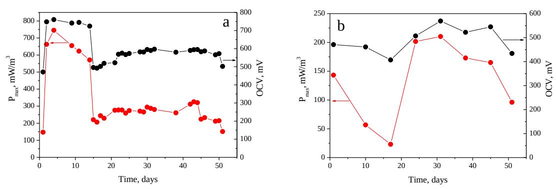

Fig. 2. Variation of OCV and maximum power density obtained with: a) MFC 1; b) MFC 2.

Interesting features were obtained in the control MFC experiment. The highest maximum power density of 1.87 W/m^3 was achieved with the sauerkraut juice taken at the 10th day of the fermentation process. This value exceeds 2.5 times that obtained with MFC 1 (Fig.3), which indicates some differences in the culture development, when it is performed in a bioreactor with a MFC. Most probably, these differences are connected with cell inhibition effects in the case of MFC, which has a volume much smaller than that of the fermentor. The tendency to drastic lowering of the maximum power at the second half of fermentation in comparison to the values recorded at the first half was also observed in the control experiment.

The ability for continuous electricity generation was demonstrated by the experiment performed with MFC 2. During the whole experiment duration the MFC was loaded with a constant external resistance ($R_{ext.}$=1 kΩ), except when polarization measurements by stepwise change of the load resistance were carried out. The variation of the generated current densities with time is shown in Fig. 4.

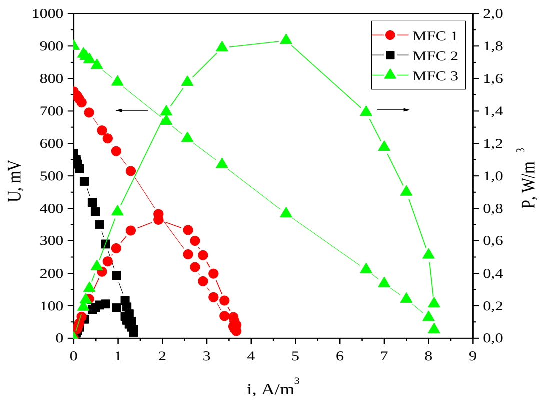

Fig. 3. Optimal polarization and power curves obtained during three MFC experiments.

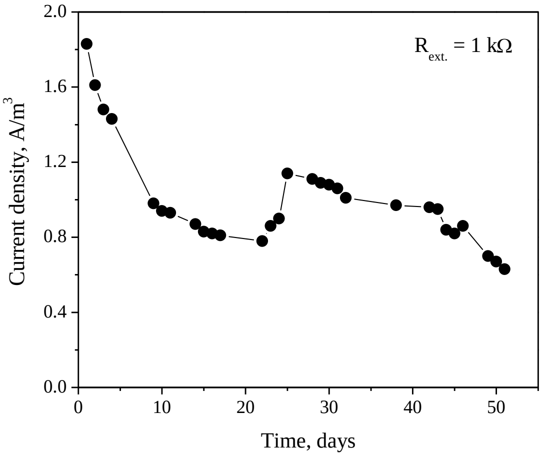

Fig. 4. Variation of generated current with time.

The measured terminal voltage reached a stable value few minutes after the circuit was closed through the external resistance. The highest current value was registered at the first day of the experiment. A steep decrease of the current was observed till the 9th day, after which the current continued to diminish with a slower rate. After three weeks, however, it began to restore and stabilized at 1.05±0.10 A/m^3 for eighteen days. A subsequent current fall down to the end of experiment was observed.

Comparing the results obtained by all MFC experiments, some charateristic features could be pointed out. Generally, the whole process could be divided into several distinct stages.

In the case when the system was not permanently disturbed (MFC 1), the OCV and maximum power values initially increased, reaching maxima at the fourth day of cultivation. This initial period of adaptation may be assigned to the first phase of fermentation, where anaerobic bacteria such as *Klebsiella* and *Enterobacter* lead the fermentation, and begin producing an acidic environment that favours later bacteria [11]. During the next period corresponding to the second fermentation phase, in which the acid levels become too high for many bacteria, and *Leuconostoc mesenteroides* and other *Leuconostoc spp.* take dominance, the MFC outputs slightly decreased but remained relatively high. The end of this stage was traced out by a sharp fall down of the electric parameters (OCV and power density) two weeks after the beginning of the experiment. Lower but relatively stable output values in comparison with those obtained during the second stage were observed along the third one. These results are not suprising having in mind that in the third fermentation phase various *Lactobacillus* species including *L. brevis* and *L. plantarum* ferment any remaining sugars, further lowering the pH [11, 12].

Three stages in the process progress could be also distinguished from the current-time plot (Fig.4), obtained with the continuously loaded MFC 2. In this case, however, a steep drop of the electrical parameters was observed during the first stage in contrary to the increase in OCV and maximum power attained with MFC 1. This result could be explained taking into account that the system under permanent load had no acclimation period and the microorganisms tried to recover the energy required for their own growth and development in a competition with the continuous electricity flux. This also explains the retardation of the first and the second stages, as well as the much lower OCV and power values obtained by polarization curve analysis in comparison with those achieved with MFC 1 and in the control experiment.

In all cases, a drop of MFC outputs was observed at the end of experiments. We suppose that this is most probably due to exhaustion of the carbohydrate source and the gradual dying away of the culture.

CONCLUSIONS

Electricity generation was achieved by using sauerkraut juice as an anolyte in double-chamber MFCs. The energy recovery process could be performed continuously but the obtained outputs depend on the specific features of the fermentation phases.

Based on the obtained results in this study, further investigations aiming at the development of biosensors for monitoring of processes during sauerkraut production are feasible.

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ГЕНЕРИРАНЕ НА ЕЛЕКТРИЧЕСТВО ПО ВРЕМЕ НА ФЕРМЕНТАЦИЯ НА ЗЕЛЕ

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(Резюме)

Възможността за използване на зелев сок като анолит в микробиологичен горивен елемент (МГЕ) бе доказана от нас в предишно изследване. В настоящата работа са представени резултатите от 50-дневни експерименти, обхващащи целия период на процеса на ферментация на зеле. Чрез циклична волтамперометрия бе проследено изменението на електрохимичното поведение на зелев сок, свързано с последователното редуване на различни доминиращи микробиални видове в смесената микрофлора, както и натрупването на междинни и крайни метаболити. Най-висока плътност на мощността от 1.87 W/m^3 бе постигната при използване като анолит в МГЕ на зелев сок в начална фаза на ферментацията, когато в средата доминират хетеро-ферментативни микробиални видове. Максималната плътност на мощността на МГЕ с постоянно свързано товарно съпротивление, обаче, бе получена след един месец работа, когато е налице забавено развитие на хетеро-ферментативните млечно-кисели бактерии и тяхната замяна с хомо-ферментативни бактерии. Относително постоянна плътност на тока от 1.05±0.10 A/m^3 бе генерирана за период от 2 седмици през по-късните етапи на ферментацията.