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Urine microbial fuel cells in a semi-controlled environment for onsite urine pre-treatment and electricity production

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HIGHLIGHTS

- Continuous averaged power density of 23 mW m^{-2} was produced for more than 120 days.
- COD and TOC removal was observed concomitantly with power production via anodic oxidation.
- Bacterial cross-over inside MFC was low when electrically connected in series or parallel.
- A large diversity of microorganisms was observed on the anodes and in solution.

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ABSTRACT

Microbial fuel cell (MFC) systems have the ability to oxidize organic matter and transfer electrons to an external circuit as electricity at voltage levels of < 1 V. Urine has been shown to be an excellent feedstock for various MFC systems, particularly MFCs inoculated with activated sludge and with a terracotta ceramic membrane separating carbon-based electrodes. In this article, we studied a MFC system composed of two stacks of 32 individual cells each sharing the same anolyte. By combining the current produced by the 32 cells connected in parallel and by adding the potential of both stacks connected in series, an average power density of 23 mW m^{-2} was produced at an effective current density of 65 mA m^{-2} for more than 120 days. [NH_3], TIC, COD, and TOC levels were monitored frequently to understand the chemical energy conversion to electricity as well as to determine the best electrical configuration of the stacks. Archaeal and bacterial populations on selected anode felts and in the anolyte of both stacks were investigated as well. Indicator microorganisms for bacterial waterborne diseases were measured in anolyte and catholyte compartments to evaluate the risk of reusing the catholyte in a non-regulated environment.

1. Introduction

Energy recovery from waste is a major challenge at a time in which the Earth's resources are increasingly strained by human exploitation [1]. For instance, a 2012 special issue of *Science* focused on “Working with Waste” to minimize the use of raw materials [2]. One attractive way to recover part of the estimated $1.5 \cdot 10^{11}$ kWh of chemical and physical energy lost from the wastewater rejected annually in the United States, is through the use of respiration of microbes in microbial electrochemical technologies [3] such as microbial fuel cells (MFCs). However, efficiently recovering useful amounts of energy from sewage at large scale treatment plants, is —at present— a suboptimal process because the nutrients containing most of the chemical energy of the wastewater have been highly diluted in the sewers [4]. The key is then to recover the chemical energy close to the source (*e.g.*, the toilet) before dilution. Urine-diversion toilets, with urine collection systems, have been employed in certain parts of the World, but even though urine is pathogen-free for healthy individuals, its potential contamination with fecal material [5] and its high ammonia and mineral content often prevent it from safe and user-friendly nutrient recovery in peri-urban and urban communities [6]. It has previously been reported that urine can successfully be used as a direct feedstock for certain microbes [7] that will oxidize some of its nutrients and transfer electrons to an inert substrate via direct or indirect processes as the anodic part of a MFC system [8,9]. This direct energy recovery and conversion to electricity from urine has shown promising results in standalone MFC systems [7,10] with a high power production per biomass for terracotta ceramic MFCs [11]. Such systems can also be installed in an onsite self-

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contained human waste treatment system relying on electrolysis to remove nitrogen, chemical oxygen demand (COD), pathogens, and to recover phosphorus [12]. MFC systems can also be used as a pre-treatment for COD and Total Organic Carbon (TOC) removal of urine coming from waterless urinals (Fig. S1). In this article, we investigate the operation of a MFC system for the pre-treatment of human urine by anodic microorganisms with electrical energy recovery. While this usage of MFC can lower the energy cost for treating human waste, it can also recover electrical energy in order to divert the urine flow, making this approach an overall energy gain for the entire onsite self-contained human waste treatment system.

2. Materials and methods

2.1. MFC stacks

The two versions of a similar design of MFC stacks employed in this study were installed in a public restroom on the campus of the California Institute of Technology (Caltech) in Pasadena (California, USA). The differences in the design are highlighted when necessary. Version A was used for the bacterial cross-over and current efficiency characterizations. Version B was used for long term monitoring with electrical energy harvesting.

Two MFC stacks for each version consisted each of 32 individual cells per stack (Fig. 1a) separated evenly and suspended in a rectangular tank connected to a water-free urinal (Fig. 1b). A gravity-driven cross-flow through each stack was made possible by placing the input and output connection at the outermost parts of the rectangular tank (Fig. 1c). In normal operation, the input of the top stack was connected to an equalization tank equipped with a level sensor commanding a pump. About 3.5 L of the urine drained from the water-free urinal were pumped when the level of urine in the equalization tank reached a certain height. The residence time of urine in the equalization tank could vary from few hours to few days as shown by the recorded feeding intervals in Fig. 2. The output of the top stack was connected to the input of the bottom stack with two 90° bent pipes to minimize cross-over between the top and the bottom stack. The output of the bottom stack drained by gravity into a tank for further processing.

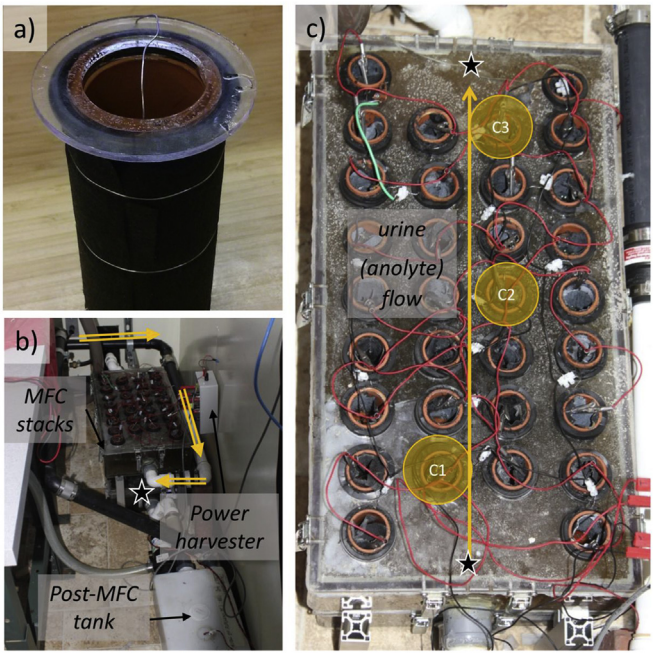

Fig. 1. a) Picture of an empty terracotta microbial fuel cell with the anode supported by a nickel-chromium wire. b) Two MFC stacks on top of each other fed by gravity (the output of the top stack is connected to the input of the bottom stack at the outermost parts of the rectangular tank) and installed behind a water-free urinal on Caltech campus. c) Top view of the top MFC stack (version A) with direction of the gravity-fed urine flow through the system. Cells C1, C2, and C3 used for catholyte sampling for microbial testing (Table 1) are highlighted. Sampling points for the anolyte in top and bottom stacks are marked with a star.

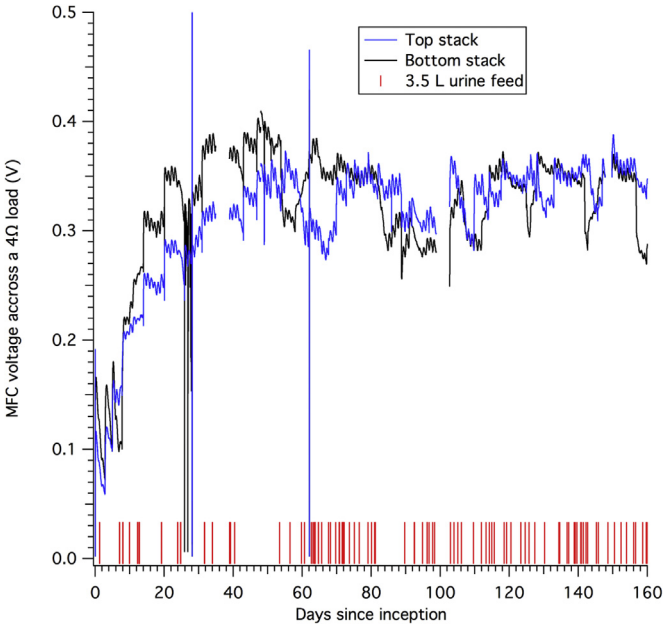

Fig. 2. Voltage across the bottom and top stack (version B), each connected to a separate 4Ω individual load. Recorded urine feeding events are represented with vertical red bars. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The cells in both versions A and B were similar to the ones described by Salar-García *et al.* [10]: each cell had a terracotta tubular ceramic tube of 150 mm length and 42 mm internal diameter (50 mm outer diameter) with an unknown pore size (Weston Mill Pottery, Newark, UK) open to air in its center and acting as an ion-conductive separator between anode and cathode. Each anode was 1000 mm by 260 mm carbon veil (loading 20 g m^{-2}, PRF Composite Materials, Dorset, UK) folded in half along its length to make 1000 mm by 130 mm and wrapped around the outside surface of the terracotta tubular ceramic tube. This was held in place by a stainless-steel wire. The wire was physically holding the electrode against the terracotta tube and acted as a current collector connected directly to the other anodes via alligator clips and metal wires (version A) or through an electrical bus bar attached to the stack acting as the anodic current collector (version B). The cathode was a 140 mm by 130 mm carbon veil with micro pores described elsewhere [13]. The cloth was rolled along its length (140 mm) and placed inside the terracotta tube in a manner intended to maximize the contact with the ceramic wall while reaching the bottom of the tube. Alligator clips connected to each other (version A) or to a metal bus bar cathodic current collector (version B) were used for electrical contact with the cathode cloth.

The inoculation period was similar for version A and version B and lasted approximately 24 days. Each stack was first inoculated with 10 L of a 1:1 solution of human urine and activated sludge from a local domestic wastewater treatment plant treating mostly domestic wastewater (San José Creek Water Reclamation Plant, Whittier, California, USA) for 3 days. After the initial addition, 3–6 L of urine were added to each stack at regular intervals (Fig. S2). The stacks were drained of the same volume before urine addition. During the inoculation, the anodes and cathodes were connected to a 4 Ω load, and voltage across the load was recorded on a continuous basis via an automatic data logger, *vide infra*. The inoculation period was stopped when the voltage across the