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# Solid phase bio-electrofermentation of food waste to harvest value-added products associated with waste remediation

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ABSTRACT

A novel solid state bio-electrofermentation system (SBES), which can function on the self-driven bioelectrogenic activity was designed and fabricated in the laboratory. SBES was operated with food waste as substrate and evaluated for simultaneous production of electrofuels viz., bioelectricity, biohydrogen ($H_2$) and bioethanol. The system illustrated maximum open circuit voltage and power density of 443 mV and 162.4 mW/m$^2$, respectively on 9th day of operation while higher $H_2$ production rate (21.9 ml/h) was observed on 19th day of operation. SBES system also documented 4.85% w/v bioethanol production on 20th day of operation. The analysis of end products confirmed that $H_2$ production could be generally attributed to a mixed acetate/butyrate-type of fermentation. Nevertheless, the presence of additional metabolites in SBES, including formate, lactate, propionate and ethanol, also suggested that other metabolic pathways were active during the process, lowering the conversion of substrate into $H_2$. SBES also documented 72% substrate (COD) removal efficiency along with value added product generation. Continuous evolution of volatile fatty acids as intermediary metabolites resulted in pH drop and depicted its negative influence on SBES performance. Bio-electrocatalytic analysis was carried out to evaluate the redox catalytic capabilities of the biocatalyst. Experimental data illustrated that solid-state fermentation can be effectively integrated in SBES for the production of value added products with the possibility of simultaneous solid waste remediation.



## 1. Introduction

In the present energy-based society, the value of any energy-rich matter is raising. Thus, high organic load in wastewaters is no longer seen as waste, but considered as a valuable energy resource. Today, methane is primarily obtained from the biogas of traditional anaerobic digesters, but its conversion into electricity via combustion is not very efficient (Motte et al., 2013). Direct electricity generation from wastewater treatment using bioelectrochemical systems (BES) is advantageous, because thermodynamic conversion step is not necessary (Venkata Mohan et al., 2007, 2010; Huang and Logan, 2008). BES is a hybrid bioelectrochemical device, which directly transforms energy stored in chemical bonds of substrate to electrical energy via bioelectrochemical reactions mediated by microorganisms as biocatalyst (Rahimnejad et al., 2011; Wu et al., 2012). Microorganisms extract energy required to build biomass (anabolic process) from redox reactions (catabolism) through electron donor/acceptor conditions. In recent years BES has emerged as a promising yet challenging technology for the recovery of energy from waste besides its treatment and is gaining importance due to its sustainable nature (Min et al., 2005; Moon et al., 2006; He et al., 2007; Kumlanghan et al., 2007; Sevda et al., 2013; Chandrasekhar and Venkata Mohan, 2012). The process provides dual benefits of wastewater treatment and access to cheap and environmental friendly energy.

One third of the food produced globally for human consumption is wasted yearly (Gustavsson et al., 2011). The overall amount of food wasted and lost worldwide corresponds to approximately 1.3 billion tonnes. This quantity includes all sorts of food, such as roots and tubers, oilseed and pulses, cereals, fruits and vegetables, meat, seafood, milk and eggs (Gustavsson et al., 2013). Food based waste generated from canteen operations is one of the most prominent and highly biodegradable solid waste (Venkateswar Reddy et al., 2011). Regardless of the food wasted, it is either treated or disposed in landfill sites in order to prevent environmental inconvenience. Elimination of food waste by dumping into landfill sites is inapt, as it causes serious health problems in densely populated areas (Cuéllar and Webber, 2010; Zilbermann et al., 2013).

Several studies depicted the possibilities of energy production from food waste by anaerobic digestion and incineration, or

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**Nomenclature**

| | | | |
|---|---|---|---|
| AB | acidogenic bacteria | OCV | open circuit voltage |
| BES | bio-electrochemical systems | PD | power density |
| CA | chronoamperometry | Q | charge |
| CD | current density | RDAP | relative decrease in anode potential |
| CDP | cell design point | $R_E$ | external resistance |
| CHP | cumulative $H_2$ production | RE | reference electrode |
| COD | chemical oxygen demand | $R_I$ | internal resistance |
| CV | cyclic voltammetry | $R_p$ | polarization resistance |
| DPV | differential pulse voltammetry | SBES | solid state bio-electrochemical system |
| DSW | designed synthetic wastewater | SSF | solid state fermentation |
| $e^-$ | electron | TDS | total dissolved solids |
| GPES | general purpose electrochemical system | TS | total solids |
| Hydrogen ($H_2$) | biohydrogen | TSS | total suspended solids |
| HPLC | high performance liquid chromatography | UASB | up-flow anaerobic sludge blanket reactor |
| $I$ | current | VFA | volatile fatty acids |
| LSV | linear sweep voltammetry | | |
| MFC | microbial fuel cell | | |

utilization of food waste as feed for pigs and cattle in order to close the nutrient loop (Sayeki et al., 2001; Shin and Youn, 2005; De Gioannis et al., 2013; Li et al., 2010; Kim et al., 2013; Dahiya et al., 2015). This waste can also act as good substrate for anaerobic digestion process due to its highly biodegradable organic content (Lim et al., 2000; Kim et al., 2006; Venkateswar Reddy et al., 2011; Ruggeri et al., 2013). Solid state fermentation (SSF) showed promising results in the production of various types of products including food and food ingredients, agro-industrial products and pharmaceutical products (Pandey, 2000). For some specific products, SSF offers higher yields and better product spectra (Ishida et al., 2000; De Vrije et al., 2001). Biodegradable organic matter present in food waste can be effectively utilized for energy recovery in the form of bioelectricity by integrating SSF with BES (Venkata Mohan and Chandrasekhar, 2011a). Nevertheless, within a short period after start-up of BES operation, edible oil forms a thin layer between substrate and electrode (anode) surface hindering direct contact between anode and anodophilic biocatalyst in turn interfering with electricity generation (Venkata Mohan and Chandrasekhar, 2011a). If properly designed BES can assist direct conversion of solid waste through SSF and consequently make the process sustainable for successful waste management.

Therefore, the present study was designed to evaluate the function of solid state bio-electrochemical system (SBES) for the recovery of bio fuels in the form of bioelectricity, biohydrogen ($H_2$) and bioethanol simultaneously by integrating SSF of food waste. Based on the output obtained from the previous study (Venkata Mohan and Chandrasekhar, 2011a), in the present study, electrodes (anode and cathode) were vertically placed to avoid interference. Bioelectricity, $H_2$ and ethanol production with the function of time were evaluated. The fate of individual volatile fatty acids (VFA) was studied during the SBES operation. Cyclic voltammetry (CV) was applied to assess the electron discharge properties of the biocatalyst. Bio-electrocatalytic assessment was done through Tafel analysis and the results were interpreted in terms of redox Tafel slopes and polarization resistance, during SBES operation.

## 2. Materials and methods

### 2.1. Composite food waste

Food waste collected from the institute canteen was grinded and used as solid feed for the operation of SBES. The solid food waste was composite in nature majorly comprising of boiled rice followed by vegetable peelings, cooked vegetables, un-cooked vegetables (spoiled), cooking oil, etc. with a water content varying between 10% and 15%. The physic–chemical characteristics of the food waste prior to feeding were evaluated and it was noticed that it had high organic content (pH, 6.8 ± 0.4; TSS, 31 ± 0.6 g/l; TS, 42 ± 0.9 g/l; TDS, 11.2 g/l; VFA, 8.4 g/l; COD, 380 g/l; carbohydrates (total), 68.5 g/l; oil content, 38 g/l). Prior to feeding the oil fraction of the waste was separated by gravity-separation mechanism (Venkata Mohan and Chandrasekhar, 2011a). Pre-characterized substrate was stored in airtight container and preserved in a refrigerator at 4±.5 °C to avoid spoilage.

### 2.2. Bio-electrochemical system architecture and operation

In this study, a single chambered solid state bio-electrochemical system (SBES) with air-cathode was designed and fabricated in the laboratory (Fig. 1). SBES was operated with non-catalyzed graphite electrodes (5 × 5 cm; 0.5 cm thick; surface area 60 $cm^2$) as anode and cathode. The design was modified by placing the electrodes vertically, instead of placing horizontally (Venkata Mohan and Chandrasekhar, 2011a) in order to avoid the interference of residual oil content. One side of the cathode was vertically immersed in food waste (electrolyte) and the other side was exposed to air, while the anode was completely dipped in the substrate. Copper wires attached to the electrodes through epoxy sealant were used to provide connection. Provisions were made in the design for wire input, sampling ports and inlet and outlet ports. The reactor had a total/working volume of 400/300 ml and was operated at room temperature (30 ± 1 °C) in fed-batch mode, with a total cycle period of 30 days. The fuel cell was closed to maintain strict anaerobic microenvironment throughout the process.

Reactor was fed with solid state food based canteen waste (270 ml) along with 30 ml (10% v/v) of tap water to maintain moisture content and to enhance the conductivity of anolyte (substrate). Prior to feeding, pH of the food waste was 6.8 ± 0.1 and was adjusted to 7 1 N NaOH solution.

### 2.3. Anaerobic consortia

Anaerobic mixed culture from full scale hydrogen producing UASB reactor was used as biocatalyst in SBES (Venkateswar Reddy et al., 2011). Prior to inoculation, the mixed culture was washed twice in saline buffer (6000 rpm, 22 °C) and enriched in designed synthetic wastewater [DSW (in g/l), Glucose, 3.0;