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# Low-temperature microbial and direct conversion of lignocellulosic biomass to electricity: Advances and challenges

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ABSTRACT

Conversion of lignocellulosic biomass to electricity using fuel cell technologies is a promising but challenging research topic for sustainable electricity production. This is because that lignocellulosic biomass generally cannot be directly used as a fuel for electricity generation in a conventional fuel cell with high efficiency. Typical fuel cells that can convert lignocellulosic biomass to electricity under mild conditions ( < 100 °C) include microbial fuel cells (MFC) and novel direct biomass fuel cells (DBFC) such as that mediated by polyoxometalates (POMs) developed recently. However, the efficiency and power output for these low-temperature fuel cells still need to be improved for practical applications. In this review, we focus on the research advances of electricity generation in fuel cells that can be operated at low temperatures. More specifically, we discussed the progress, challenge and perspectives of biomass-fueled MFCs. Recent interesting researches on DBFC were also highlighted in terms of the efficiency, principles, and technological obstacles. As concluded in this work, lignocellulosic biomass is a promising feedstock for fuel cells because it is renewable, carbon neutral, and sustainable. However, the power density of lignocelluose-fueled MFC are usually far below that required for commercial applications. Improving fermentable sugar release from lignocellulosic biomass and increasing the cell output power are the main research points. DBFC can obtain a high theoretical exergy recovery; however, it is still in its early stage of development with low efficiency. More research should be focused on the electrode development, cell design, parameter optimization, process integration, as well as understanding fundamental process mechanisms.

## 1. Introduction

Electricity is one of the essential forms of energy that dictates quality of life in modern society. Demand for electricity continues to grow as a result of the increase in global population and development of third-world nations [1]. In early days, electricity was generated using hydro power at remote dams or fossil fuels through combustion to drive turbines [2]. Fossil fuels are still the major energy source for electricity production. Approximately 66% of electricity is produced from fossil fuels, including 33% from coal and 33% from natural gas in 2015 in the United States (US Energy Information Administration, http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3, last accessed July 20, 2016). However, conventional fossil-fuel-driven power plants are facing increased challenges due to emissions of pollutants and greenhouse gases. Thus, sustainable and environmentally friendly pathways for alternative electricity production using renewable resources must be developed.

Lignocellulosic biomass is a renewable natural resource that can be sustainably produced in large quantities in many regions around the world. The United States alone has the potential of sustainably producing 1.3 billion dry tonnes of lignocellulosic biomass annually from forest and agricultural lands [3]. This is equivalent to 2 trillion kWh of electricity (assuming 30% conversion efficiency from thermal energy to electricity), which is approximately 50% of the total U.S. electricity production in 2014. Electricity generation from lignocellulosic biomass has already been in commercial practice using combustion or gasification together with a steam or gas turbine (Fig. 1). However, distributed operation at relatively small scale is preferred due to the low energy density of lignocelluloses.

Fuel cell technology attracted great interest in recent years for

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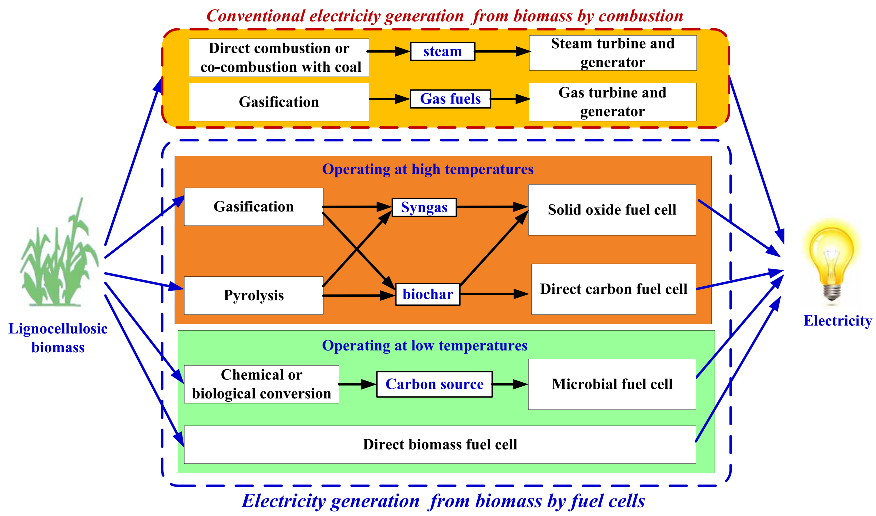


**Fig. 1.** Different pathways for electricity production from lignocellulosic biomass.

clean, portable, alternative electricity production and is suitable for a variety of applications. Lignocellulosic biomass-energized fuel cells can be classified into two major groups: indirect biomass fuel cells (IDBFC) and direct biomass fuel cells (DBFC). IDBFC, which has been intensively studied in recent years, refers to fuel cell technology that requires pre-converting biomass to usable fuels such as sugars (e.g., glucose and xylose), syngas, biogas, or biochar, for subsequent electricity generation in fuel cells [4]. IDBFC included solid oxide fuel cells (SOFC) and direct carbon fuel cells (DCFC) which are operated at high temperatures, as well as microbial fuel cells (MFC) operated at low temperatures. DBFC is a new technology that can produce electricity using biomass directly as fuel without preconverting or processing. DBFC technology is new with only limited research being carried out [5–8]. Low temperature fuel cells offer many advantages for many distributed applications, in this review we, therefore, focus on electricity generation from biomass via MFC and DBFC operated under mild conditions. The aim of this work is to present some basic principles, technological challenges, and future developments of these technologies.

## 2. Overview of lignocellulosic biomass and low temperature biomass fuel cells

Lignocellulosic biomass generally can be divided into two categories: woody biomass (including forest harvest residues and dedicated short-rotation woody crops) and herbaceous biomass (including agriculture residues such as straw and corn stover and energy crops such as switchgrass). Ligncellulosic biomass is renewable, carbon neutral in terms of reduction of $CO_2$ emission, and sustainable [9]. The major elemental compositions of lignocelluloses are C, H, O, N, P, and S. The elements C, H, and O mainly come from the three major components of lignocelluloses (cellulose, hemicelluloses, and lignin); N, P, and S mainly come from the minor component, such as protein. Dry lignocelluloses commonly have a C content of approximate 50%, lower than that of coal (75–90%) , and an O content of about 45%, higher than that of coal ( < 20%). Lignocellulosic biomass has much higher ratios of H/C and O/C than those of fossil fuels. Thus, the heating value of lignocellulosic biomass is lower. For example, bituminous coal generally has a higher heating value (HHV) of 26 MJ $kg^{-1}$, while the HHV of lignocelluloses biomass is usually less than 20 MJ $kg^{-1}$ [10,11]. Moreover, lignocellulosic biomass usually has high moisture content. Freshly cut wood typically contains 50% water by weight [12].

Lignocellulosic biomass is a complex natural material comprising three major components—cellulose, hemicelluloses, and lignin—and some minor components, such as extractives, protein, and ash. The major components account for more than 80% of the total dry weight of lignocelluloses [13,14]. However, different species of plants significantly differ in the proportions of the major components [15]. Even different parts of the same plant have different proportions of the major components. Woody biomass contains more cellulose and lignin, whereas herbaceous biomass has higher contents of hemicelluloses (mainly xylan), extractives, and ash. Generally, woody biomass contains 40–50% cellulose, 15–20% hemicelluloses, 20–35% lignin, and 0.2–1.1% ash, whereas herbaceous biomass contains 20–40% cellulose, 20–40% hemicellulose, 10–20% lignin, and 2–17% ash. Cellulose is a polysaccharide consisting of a linear chain of several hundred to more than 10,000 $\beta$ (1→4) linked D-glucose units. Hemicelluloses are heteropolymers of several monosaccharide groups and uronic acid groups, including hexoses such as D-glucose, D-galactose, and D-mannose; pentoses such as D-xylose and L-arabinose; uronic acids such as D-glucuronic acid, 4-O-methyl-D-glucuronic acid, and D-galacturonic acid; and to a lesser extent, L-rhamnose, L-fucose, and various O-methylated neutral sugars [16]. Lignin is an aromatic polymer composed of three basic monomeric units: *p*-hydroxyphenyls (H), guaicyls (G), and syringyls (S), which vary between species and cell tissue type [17]. Lignin has higher carbon content than cellulose and hemicelluloses, thus higher heating value. More details on the structures of cellulose, hemicelluloses, and lignin can be found in literatures [16,18,19].

In the three types of IDBFC (Fig. 1): microbial fuel cells (MFC), solid oxide fuel cells (SOFC), and direct carbon fuel cells (DCFC), only MFC can be operated at low temperatures. MFC use cellulose-degrading organisms with the addition of exogenous cellulase enzymes to produce electricity [20–23]. Lignocellulosic biomass need to be hydrolyzed to sugars to achieve high efficiency by microorganisms. The diversity of microorganisms in MFCs makes it possible to achieve near complete utilization of all biomass components, including lignin. DBFC can produce electricity from lignocelluloses directly with less exergy destruction because no external processing is required. Due to the complex structure of lignocelluloses and lack of efficient catalysts to effectively oxidize C-C bonds, DBFC may produce low power output. Research on DBFC is still in its early stage and this type of fuel cell shows great promising.

The performance of a fuel cell is usually characterized by several output parameters, such as open circuit voltage (OCV), current density (CD), power density (PD), and coulombic efficiency (CE). These terms are defined as follows: open circuit voltage is the maximum voltage available from a fuel cell at zero current in V or mV; current density is the current per unit area of electrochemical-active electrode (anode) in mA $cm^{-2}$; power density is power output per unit area or volume in mW $cm^{-2}$ (or W $cm^{-2}$) coulombic efficiency, also called Faradic effi-