Journal of Energy Chemistry 25 (2016) 191–198

Contents lists available at ScienceDirect

Journal of Energy Chemistry

journal homepage: www.elsevier.com/locate/jechem

http://www.journals.elsevier.com/journal-of-energy-chemistry/

Review

Microbe-derived carbon materials for electrical energy storage and conversion☆

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ARTICLE INFO

Article history:
Received 28 September 2015
Revised 2 November 2015
Accepted 2 November 2015
Available online 17 December 2015

Keywords:
Microbe
Carbon materials
Supercapacitor
Lithium-ion battery
Oxygen reduction reaction
Hydrogen evolution reaction

ABSTRACT

Microbes are microscopic living organisms that surround us which include bacteria, archaea, most protozoa, and some fungi and algae. In recent years, microbes have been explored as novel precursors to synthesize carbon-based (nano)materials and as substrates or templates to produce carbon-containing (nano)composites. Being greener and more affordable, microbe-derived carbons (MDCs) offer good potential for energy applications. In this review, we describe the unique advantages of MDCs and outline the common procedures to prepare them. We also extensively discuss the energy applications of MDCs including their use as electrodes in supercapacitors and lithium-ion batteries, and as electrocatalysts for processes such as oxygen reduction, oxygen evolution, and hydrogen evolution reactions which are essential for fuel cell and water electrochemical splitting cells. Based on the literature trend and our group's expertise, we propose potential research directions for developing new types of MDCs. This review, therefore, provides the state-of-the-art of a new energy chemistry concept. We expect to stimulate future research on the applications of MDCs that may address energy and environmental challenges that our societies are facing.

1. Introduction

Modern human societies heavily rely on the consumption of nonrenewable fossil fuels for powering engines and producing electricity. However, the depletion of fossil fuels have triggered great economic concerns, and the generation of huge amounts of carbon dioxide from burning fossil fuels escalated environmental crises like global warming [1,2]. A promising approach to address these issues is the vast utilization of electrical energy converted from renewable sources such as solar, wind, geothermal, hydroelectric, tidal energy, and biomass [3–6]. Although these sources are already in use for decades, we still fail to maximize all their potential due to a variety of issues. Among the technological and economic issues associated with renewable energy sources, there are two key issues worth mentioning.

First, the electricity generated by renewable sources and the daily energy demands often fluctuate over time [7]. Thus, in order to obtain a reliable power supply that can meet the demand without continuously generating energy excess, we need affordable energy storage devices that can effectively store the excess renewable energy output whenever available [8]. However, present energy storage systems are either ineffective or expensive to rationalize their common usage for such a purpose. Second, for most engines, the consumption of fossil or chemical fuels with high specific energy density is still more favorable than the use of electrical energy [2,9]. Actually, being an efficient energy carrier with one of the highest specific energy values among all chemical fuels (142 MJ/kg) and with an added benefit of zero-emission, hydrogen is a viable alternative [10]. However, as in other chemical fuels, we still need to develop better processes for efficient conversion of the chemical energy of hydrogen into electrical energy, which is typically conducted by fuel cells and electrochemical water splitting cells [1]. Unfortunately, similar to the problems of energy storage systems mentioned earlier, both fuel cells and water splitting cells suffer from either low efficiency or high cost. To address both of these two key issues, a new family of carbon materials produced using microbes as precursors called microbe-derived

☆ This work was supported by the Ministry of Education, Singapore (2013-T1-002-132) and the iFood program of Nanyang Technological University. The corresponding author, Yuan Chen, also acknowledges The University of Sydney for financial support.

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http://dx.doi.org/10.1016/j.jechem.2015.12.001
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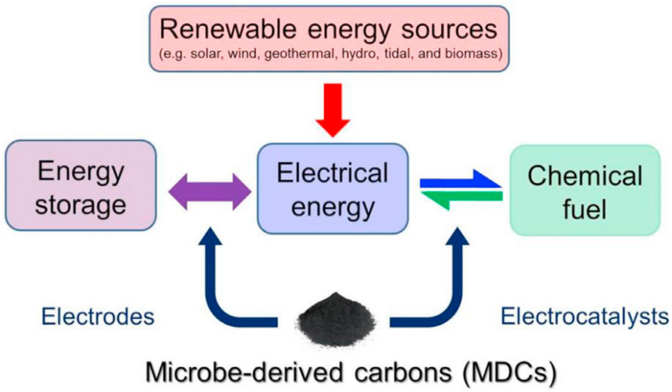

Fig. 1. Possible roles of MDCs as electrodes for electrical energy storage and as electrocatalysts for electrical energy conversion systems.

carbons (MDCs) can be exploited either as electrode materials or electrocatalysts (Fig. 1).

In this review, we first introduce the fundamentals of devices and conventional devices and carbon materials involved in electrochemical energy storage and conversion. Next, we explain the unique advantages of MDCs as new carbon materials. We subsequently describe the typical procedures for converting microbes into MDCs. Then, we thoroughly discuss various latest applications of MDCs as electrodes in supercapacitors and lithium-ion batteries and as electrocatalysts for electrochemical processes like oxygen reduction, oxygen evaluation, and hydrogen evolution reactions which are the basis of fuel cells and electrochemical water splitting cells. Lastly, we propose a variety of potential research directions for MDCs based on the literature trend and our group's own expertise. We ultimately aim to provide the state-of-the-art account of this emerging topic and to encourage future research on the use of microbes as sustainable precursors or templates in producing carbon (nano)materials or (nano)composites beneficial for the development of practically viable electrical energy storage and conversion systems.

2. Devices and carbons for electrochemical energy storage and conversion

2.1. Devices used for electrochemical energy storage and conversion

In order to overcome two key issues briefed in the Introduction, four types electrochemical devices are intensively studied: (1) supercapacitors and (2) lithium-ion batteries for electrical energy storage, (3) hydrogen fuel cells for converting hydrogen to electrical energy, and (4) electrochemical water splitting cells for transforming electrical energy into hydrogen.

As sketched in Fig. 2(a), supercapacitors store electrical energy by the physical adsorption of electrolyte ions on the surfaces of electrode materials (a.k.a. electrochemical double layer capacitance, EDLC) and/or by reversible redox reactions, intercalation or electrosorption at or near the surface of some electrode materials (called pseudocapacitance) [11]. Lithium-ion batteries (Fig. 2b), on the other hand, store electrical energy by moving lithium ions between an intercalated lithium compound in cathode and a carbon material based anode. The electrolyte allows ionic movement during charge and discharge [12,13].

In hydrogen fuel cells (Fig. 2c), hydrogen is oxidized through hydrogen oxidation reaction (HOR) on catalysts loaded on the anode to generate hydrogen ions and electrons. Subsequently, hydrogen ions go through the electrolyte towards the cathode, while electrons travel through an external circuit producing direct current electricity. Oxygen, hydrogen ions and electrons then react by

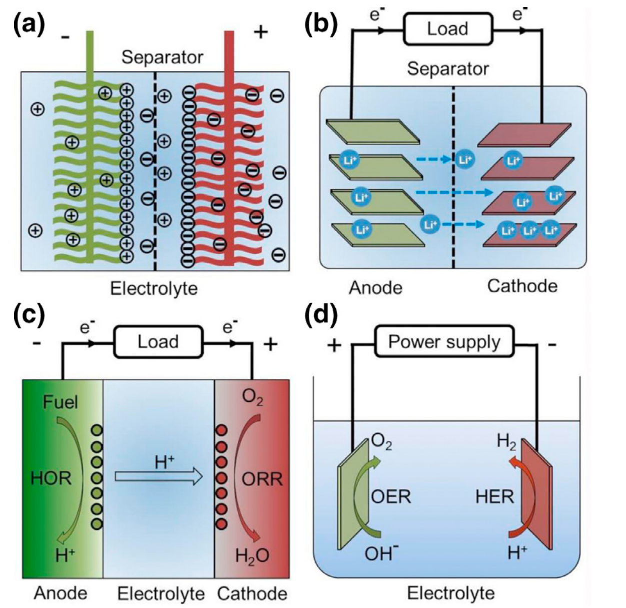

Fig. 2. Schematic illustrations of working mechanism of (a) a supercapacitor, (b) a lithium-ion battery, (c) a hydrogen fuel cell, and (d) an electrochemical water splitting cell.

oxygen reduction reaction (ORR) to form water on the cathode side of the cells [14]. Conversely, in an electrochemical water splitting cells (Fig. 2d), an electrical power source is connected to two electrodes in water. Hydrogen appears at the cathode by hydrogen evolution reaction (HER), while oxygen is generated on the anode by oxygen evaluation reaction (OER) [15,16].

2.2. Carbons used in electrochemical energy storage and conversion devices

In the electrochemical energy storage and conversion platforms explained earlier, the fundamental material used is carbon. Carbon materials (in short, carbons) form a broad class of ordered and disordered solid phase materials mostly composed of elemental carbon (C). They can be either be synthetic or natural in origin, including graphite, graphene and graphene oxide (GO), carbon nanotubes, fullerenes, carbon fibers and filaments, porous carbons, pyrolytic carbon, glassy carbon, carbon black, diamond and diamond-like carbon, and chars. All these carbons play many important roles in energy storage and conversion systems. For example, graphene, GO, carbon nanotubes, and fullerenes can assist the generation of electricity from solar energy [17–20]. Similar carbons are also helpful in various biomass conversion reactions both as catalyst supports and as active catalysts [21–24]. Carbons like activated carbon and carbon black have been widely used for electrical energy storage in supercapacitors as electrode materials [25–29] and graphite is the dominant anode materials in lithium-ion batteries [30,31]. Carbons are also utilized in electrochemical energy conversion serving either as catalyst supports or as active catalysts for ORR, OER, and HER in fuel cells and electrochemical water splitting cells [18,32–34].

Carbons possess diverse and interconnected physical and chemical properties. To achieve outstanding and reproducible performance out of carbons in energy applications, their structures should be controlled well [26–29,35,36]. For example, carbons used for supercapacitor electrodes should have large specific surface area for ion adsorption, a suitable combination of micropores and mesopores for fast ion mobility, good electrical conductivity for electron transfer, and favorable surface functionalities for