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Development of biohydrogen production by photobiological, fermentation and electrochemical processes: A review

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ABSTRACT

Production of biohydrogen has the potential to be a renewable alternative to current technologies. There are varieties of technologies for biological hydrogen production mechanisms including biophotolysis, photo fermentation, dark fermentation and hybrid biohydrogen production by electrochemical processes. In these studies, a review on the recent developments of biohydrogen production is presented. First, the theoretical principles of biophotolysis by cyanobacteria and green micro algae, as well as direct and indirect of biophotolysis process on hydrogen production are described. Secondly, practical aspects and fundamental of biological hydrogen production processes by photo and dark fermentation are reviewed. This work also involved comparison of the maximum H_2 yield, bacterial strains, operating condition, suitable substrates, and mathematical models for fermentative hydrogen production. A new hybrid biological hydrogen production processes by using the electrochemical process is then proposed. This study can also be used to improve the basic and current knowledge about the performance of the biophotolysis, fermentative and electrochemical process in producing hydrogen gas as the alternate fuel.
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1. Introduction

One of the great challenges in the coming decade is how to get new renewable energy sources that are environmentally friendly and to replace high dependency on fossil fuels. Until recently, almost all of the energy needed is derived from the conversion of fossil energy sources, such as for power generation, industrial and transportation equipment that uses fossil fuels as a source of energy. Fossil fuels are source of non-renewable energy and also have seriously negative impacts on the environment, e.g. soil, water, air, and climate. The use of fossil fuels cause excessive global climate change because emissions of greenhouse pollutants and the formation of compounds CO_x, NO_x, SO_x, C_xH_y, ash, and other organic compounds that are released into the atmosphere as a result of combustion [1,2].

Based on the above considerations, in recent years various studies has been conducted to obtain a sustainable source of energy that can replace fossil fuels and which do not have a negative impact on the environment. Hydrogen is one alternative fuel substitute for fossil fuels and is considered as an "energy carrier" with a promising future. It has a high energy content of 122 kJ/g, which is 2.75 times greater than hydrocarbon fuels [3].

Hydrogen plays a very important role and contribution in the global era that is based on clean renewable energy supplies and sustainably which will provide major contributions to the world economic growth. Hydrogen fuel is environmentally friendly, clean and is the most abundant element in the universe in its ionic form. Hydrogen gas is also colorless, tasteless, odorless, light and non-toxic. When its gas is used as fuel, it will not produce pollution to the air but it produces only water as its end-product when it burns [4]. Hydrogen gas which is produced by biological processes becomes very interesting and promising because they can be operated at ambient temperature and pressure with minimal energy consumption, and become more environmentally friendly [5].

According to Mohan et al. [5], hydrogen can be produced from different types of raw materials, including fossil fuels, water, and biomass. Hydrogen production from renewable sources can be obtained in different ways. There are several major renewable energy sources to produce from the water that flows, the heat from the earth, wind, solar, biomass and biological hydrogen production from microorganisms. Many microorganisms are known to produce hydrogen under certain conditions, including microalgae such as blue-green algae that use light energy to split water for hydrogen formation and cyanobacteria that usually use carbohydrates to store energy from photosynthesis to produce hydrogen from water [6].

Production of hydrogen gas from renewable biomass materials can be obtained from a variety of organic-based starch industry waste, industrial waste biodiesel, lignocellulosic materials such as wood and its products, food, household waste and others. Biological hydrogen production using carbohydrate-rich biomass as a renewable resource is one of the alternative methods where processes can take place through an anaerobic process (dark fermentation) and photosynthesis process (photo-fermentation). Dark fermentation is the conversion of organic compounds to hydrogen; it takes place in the absence of oxygen by a group of bacteria using multi enzyme systems. This process takes place in several stages, where a series of complex biochemical reactions manifested by a group of bacteria into hydrogen gas. The first step is the enzymatic hydrolysis of high molecular weight organics to water-soluble organics, and in a second step the simple organic to produce Volatile Fatty Acids (VFA), hydrogen, and carbon dioxide [7,8].

Photo-fermentation is the conversion of organic compounds to biohydrogen involving various groups of bacteria photosynthetic by a series of biochemical reactions. Photo-fermentation differs from dark-fermentation because it only occurs in the presence of light. If viewed from the perspective of economic, hydrogen production through dark-fermentation has advantages and more profitable than photo-fermentation processes because of its ability to continuously produce hydrogen and does not depend on energy provided by sunlight [9].

A new hybrid biological hydrogen production processes has been developed very recently by use of the electrochemical process. These processes include the electrolysis which is based on the concept and practice of Microbial Fuel Cell (MFC). This method needs to be added with electric potential generated by a microbial fuel cell, so as to achieve sufficient strength to release protons to hydrogen. Production of hydrogen by an electrochemical process is not limited only to carbohydrates, as in the fermentation process. Other biodegradable organic matter dissolved can be used to generate hydrogen from the complete oxidation of organic matter. Instead, by electrochemically increasing the cathode potential in a Microbial Fuel Cell (MFC), it is possible to continuously produce hydrogen assisted electron exchange by bacteria. This method greatly decrease the amount of energy needed to produce hydrogen from organic matter compared to hydrogen production from water via electrolysis [10,11].

This review focuses on literature survey carried out on the production of hydrogen by biological process. This literature study will discuss in detail about the biological hydrogen production methods including biophotolysis, photo-fermentation and dark-fermentation and hybrid biological hydrogen production by electrochemical processes.

2. Fundamentals of biological hydrogen production processes by biophotolysis

Biophotolysis is associated with plant-type photosynthesis process, formerly known as blue-green algae that uses light to split water for hydrogen formation, and takes place under anaerobic conditions. Biophotolysis indirectly involve cyanobacteria usually use carbohydrates to store energy from photosynthesis to produce hydrogen from water.

2.1. Biophotolysis of water by cyanobacteria and green micro algae

Biophotolysis process can occur in various species of bacteria and algae, for example species of bacteria and algae that can produce hydrogen through biophotolysis like photosynthetic bacteria from soil or natural water, Anabaena species Cyan bacteria, or eukaryotic alga Chlamydomonas species Reinhardt. The hydrogen gas production in a sustainable and environmentally friendly to produce clean energy from renewable resources can be obtained through biophotolysis of water by cyanobacteria and Green Micro Algae. Cyanobacteria and green algae can split water into hydrogen and oxygen molecules by using sunlight [12,13]. Mechanism of biohydrogen production through biophotolysis or photoautotrophic process is hydrogen gas formed from the water by using sunlight and CO_2 as the sole source for energy through the process of hydrogenase enzyme by bacteria and algae [14]. Fig. 1 shows the ability to photosynthesis produce H_2 under anaerobic conditions using green alga *Chlamydomonas reinhardtii*.

The advantage of biophotolysis is that, there is no requirement of adding substrate as nutrients. Water is the primary electron donor required for the production of hydrogen gas. Sunlight and CO_2 are the basic inputs needed to grow the cyanobacteria or microalga on biophotolysis process through the hydrogenase enzyme.

Production of hydrogen gas by green algae and cyanobacteria is one of the methods that produce renewable energy which does not emit greenhouse gas effect with the availability of abundant resources, namely water as substrate and solar energy as a source of energy. Thus, hydrogen gas produced could be used in a fuel cell to generate electricity as shown in Fig. 2 [15].

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