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Research perspectives on constraints, prospects and opportunities in biohydrogen production

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ABSTRACT

Hydrogen gas can be formed from sewage sludge treatment via anaerobic digestion (AD) as this sludge contains large amount of organic matters. In this review, a comprehensive attempt has been made to revisit the main updates, advantages and disadvantages surveyed in recent research (2012–2017) on fermentative hydrogen production from a variety of biomass. The main findings of this review are now stated. The biological hydrogen production processes consist of indirect and direct biophotolysis, dark fermentation, two-stage fermentation and photo-fermentation. To maximize hydrogen gas yield via such technique, the activity of hydrogen-consuming bacteria should be inhibited at the acetate and hydrogen formation stage to stop or reduce hydrogen consumption. The major constraints in biological hydrogen production processes are raw material cost, low hydrogen evolution rate and yield at large scale. Lignocellulosic materials generate low yield of hydrogen gas due to the presence of refractory lignin while food waste containing carbohydrates and starch yields more hydrogen gas. Effective pretreatment of substrates and inoculum can enhance hydrogen yield. In dark fermentation process, better performance can be obtained with pretreatment. Nitrogen sources such as yeast result in higher biohydrogen generation rate and cell growth from the presence of amino acids and proteins. In photo-fermentation, better results can be obtained by using a combination of photosynthetic bacteria and green microalgae, as it enhanced solar energy utilization. Future development such as genetic manipulation could be employed, which mainly focuses on the disruptive characteristics of endogenous genes. The efficiency of biohydrogen production can also be increased by lowering the costs of delivery, production, conversion, storage and practical applications. Apart from using biodegradable wastes, green wastes will be the mostly preferable targeted feedstock for hydrogen fermentation because of their large quantity and having simultaneous waste treatment benefit.

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Introduction

From the beginning of the industrialized era, combustion of fossil fuel is still dominating the global energy consumption of about 80% [1,2]. Additionally, the worldwide energy consumption in the last decade has increased exponentially and will continue to grow over the next fifty years [3,4], due to population increase, prosperous lifestyle, civilization, industrialization, modernization and better air quality requirement [4–6]. Most of our energy requirements are heavily derived from fossil fuels with coal accounting for 27.2%, oil 32.8% and natural gas for 20.9% for transportation and heating [7,8]. Höök and Tang [2] mentioned that after fossil fuels, 5.8% nuclear power, 2.3% hydroelectric dams and 10.2% combustible biomass and waste contribute to the worldwide energy system; however they account only for a minor share of the total primary energy requirements. Only a minor amount of global energy requirements of about 0.8% [2] is obtained from geothermal, wind and solar.

Devabhaktuni et al. [9] reported that recently, the global population from one generation to another has augmented by nearly 2 billion in most developing countries. This has resulted in an increase in energy demand and a vast population living in poverty. Based on the fact that the energy demand is proportional to industrialization [5], some developing countries will need to double their installed generation capacity to satisfy the growing demand for electricity by year 2020. From 2006 to 2030, the total energy consumption is expected to increase by 44% according to Devabhaktuni et al. [9]. However, an excessive dependence on conventional resources poses a great challenge [3,10] both to the environment and human beings due to continual rising of oil prices and increasing environmental consequences such as global warming [11] as carbon dioxide and a large factor of air pollutants are emitted during the combustion of fossil fuels [1,12]. Therefore, Kapdan et al. [13] reported that the imminent shortage of energy resources has led to the introduction of more renewable energy sources. As a result, the renewable energy technologies of biofuels, wind, photovoltaics and solar thermal are finally showing some attractions [1].

Biofuels

In particular, biofuels represent clean, eco-friendly, biodegradable, sustainable and cost competitive energy sources from renewable carbon resources. Among these, hydrogen is recognized as having the highest potential as a future energy carrier because of its reduced emission of air pollutants and greenhouse gases into the atmosphere [1,9]. Gupta [3] mentioned that hydrogen can be utilized for heating, transportation and power generation [14,15] and can replace all existing fuels which are being used nowadays. Hydrogen is generated from both renewable and non-renewable sources. However, research has so far been focused on the biohydrogen generation field, either by biological or physiochemical method [12]. Recently, the worldwide need on hydrogen is growing exponentially (12% annually) presently and contributing to a total energy market of 10% by 2025 [16].

Hydrogen as a cleaner fuel

Hydrogen has wonderful properties as clean and green biofuel. At atmospheric temperature, hydrogen is a non-toxic, odourless, colourless, tasteless and highly combustible gas with a molecular formula H_2. Being the lightest element on earth, hydrogen diffuses at a faster rate than other gases. The boiling point of hydrogen is 22.28 K, and hydrogen has a combustion energy of 120 MJ/kg and a heat capacity of 14.4 kJ/kg K [3]. Hydrogen being a valuable, colourless, odourless, poisonous, tasteless [1] and clean fuel is used in different chemical process industries, since its only product is water, and does not emit other deleterious pollutants and CO_2 in the environment when producing electricity and is truly a sustainable replacement for the dwindling fossil fuels [17,18]. Karthic and Shiny [16] outlined that in the year 2008, the total annual production of hydrogen fuel was 368 trillion cubic meters and was used mostly in the chemical industry (40%), in oil refineries (40%) and 20% in a huge variety of processes.

Up to this moment, hydrogen being the most abundant element on the planet, is formed from water, biomass, natural gas and coal. Globally, the formation of hydrogen gas is obtained from conventional resources through thermochemical processes, thermal cracking processes of natural gas and splitting of water through electrolysis [18,19]. However, the different metabolites and by-products obtained from these methods might cause harm to the environment in equally different ways. Nowadays, steam reforming of natural gas is the cheapest way to form hydrogen gas where steam at temperatures of 700–1000 °C, with a catalyst, is fed to a reactor at a pressure of 3–25 bars.

It is deduced that at the end of the process, 4 mol of hydrogen gas are formed. Therefore, in order to produce minimum environmental effects in the formation of hydrogen gas, hydrogen can also be generated biologically [16,20–22]. Skarha [22] stated that biohydrogen is the hydrogen formation from resources such as biomass or organic wastes either biologically or photo-biologically. Biohydrogen fuel has significantly certain advantages, namely, the conversion of biohydrogen in power fuel cells is two times more efficient rather than burning a biofuel in combustion engine; no air pollutants are emitted during the combustion of biohydrogen gas compared to other biofuels; biohydrogen emits CO_2 only during fermentation process, but it is more easily to be captured, hence making it carbon negative; and it has low investment cost [11,22].

Biohydrogen synthesis

The means of achieving biohydrogen is biophotolysis, dark fermentation and photo fermentation. Unarguably, biohydrogen production falls within green chemistry and green engineering concepts, which make use of a set of principles, hence showing a better way to reduce or eliminate hazardous substances while designing, manufacturing and applying chemical products [13,23]. Green chemistry and engineering involve a lower use of energy when generating a chemical product and accounts less harm to the environment and is socially acceptable [13]. Thus, the purpose of this study is to present an overview of the different processes used to

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