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Review

Photo-fermentative hydrogen production from crop residue: A mini review



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HIGHLIGHTS

- Technology of bio-hydrogen production from crop residues were reviewed.
- Pretreatment methods and substrate structure were discussed.
- Hydrogen from pure bacteria, consortia and mutants were discussed.
- Geometry, light source and mass transfer properties of bioreactor were reviewed.

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ABSTRACT

Photofermentative hydrogen production from crop residues, if feasible, can lead to complete conversion of organic substances to hydrogen (and carbon dioxide). This mini review lists the studies on photofermentative hydrogen production using crop residues as feedstock. Pretreatment methods, substrate structure, mechanism of photosynthetic bacteria growth and metabolism were discussed. Photofermentative hydrogen production from pure culture, consortia and mutants, and the geometry, light sources, mass transfer resistances and the operational strategies of the photo-bioreactor were herein reviewed. Future studies of regulation mechanism of photosynthetic bacteria, such as highly-efficient strain breeding and gene reconstruction, and development of new-generation photo-bioreactor were suggested.

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1. Introduction

The global industrial development in the past century heavily depended on consumption of fossil fuels, not only causing concerns on depletion of the nonrenewable energy source, but also leading to the global warming issue due to greenhouse gases (GHG) emission. A large portion of current fossil fuel reserves (1/3 of oil, 1/2 of natural gas, and more than 4/5 of coal) should remain unused up to 2050 to meet the 2 °C target for GHG control over the 21st century (Mcglade and Ekins, 2015). Meantime, global energy demand is still increasing to nearly doubled by year 2050 (IRENA, 2015). To reduce the GHG emission with meeting energy demand, renewable energy supplies, such as biofuels from biomass, are desired (Balan, 2014). It is estimated that biofuel in total transportation fuel would grow up to 27% in 2050 (<https://www.iea.org/newsroomandevents/pressreleases/2011/April/biofuels-can-provide-up-to-27-of-world-transportation-fuel-by-2050-iea-report-.html>)

Crop residues are produced from corn, wheat, and rice processing, with those from China contributing about 23% of corn, 18% of wheat, and 28% of rice over the globe in 2012 (FAOSTAT, 2012). About 0.5 billion dry ton of crop residues were available in China (Jiang et al., 2012). Liquid and gas fuels, such as bioethanol, biobutanol, biomethane and biohydrogen can be produced from this abundant and renewable feedstock (Karimi and Taherzadeh, 2016). Among these fuels, hydrogen has the highest energy density per mass (142 kJ/g) and produces no GHG while burning (Ghanavati et al., 2015; Hay et al., 2013).

Global hydrogen market was estimated to grow annually at a rate of 6.2% from 2011 (\$87.5 billions) to 2016 (\$118 billions), with 88% of hydrogen being produced from nonrenewable energy sources, such as natural gas, heavy oil, naphtha, and coal (Hay et al., 2013). There are efforts for bio-hydrogen production from biomass and wastewater with microorganisms. Bio-hydrogen can be produced by: (1) bio-photolysis with cyanobacteria or green algae, (2) dark fermentation with anaerobic bacteria, (3) photofermentation with photosynthetic bacteria, and (4) microbial electrolysis. During bio-photolysis process, light energy is converted to free energy of hydrogen at a low efficiency (theoretical efficiency no more than 4.6%), which limits its application to a practical system (Hallenbeck, 2012). Dark fermentation also has a drawback of low H₂ yields due to accumulation of volatile fatty acids. In contrast, photo-fermentation can use organic compounds, usually organic acids, as the substrates (Hallenbeck and Ghosh, 2009; Keskin and Hallenbeck, 2012).

Extensive reviews on dark fermentation are available; conversely, only few information on photofermentative hydrogen production from crop residues is available (Hay et al., 2013). Photofermentation bio-hydrogen production can be described by

the following formula ($\text{CH}_3\text{COOH} + 2\text{H}_2\text{O} \rightarrow 2\text{CO}_2 + 4\text{H}_2$) using acetate as the model feed substrate. Chandrasekhar et al. (2015) commented on the advantages and disadvantages for photofermentative hydrogen production. Uyar (2016) summarized the concerns for designing the photofermentative bioreactor. This mini-review focused on the research progress in photofermentative hydrogen production using crop residues as feedstocks, considering the aspects of feedstock types, pretreatment methods, photosynthetic bacteria, reactors, and operational strategies on hydrogen productivity. Perspectives for future studies in photofermentative hydrogen production from crop residues are highlighted.

2. Crop residues

2.1. Status of the crop residue resources

Agriculture and forestry are the two sources of renewable carbon sources that can be used for energy production (Chandra et al., 2012). Compared to forestry residues, agricultural waste usually has higher cellulose and hemicellulose contents and lower lignin contents, making them more favorable for bio-energy production. Annually, a large quantity of crop residue is produced in the world (Lal, 1995). The primary crop residues can be categorized into cereal crop residue, leguminous crop residue, root crop residue, and oil seeds residue. In terms of the total residue production quantity, cereals are the most important residue stream than the other three.

The main worldwide production of cereal crop residue is composed of rice straw, wheat straw, corn stover, and sugarcane bagasse (Bakker et al., 2013). Due to the different demands of the crops on climate and availability of water, the four major straws can be collected from different locations: rice straw and wheat straw are mostly produced in Asia, America is the major producer of corn stover and sugarcane bagasse (Sarkar et al., 2012). The composition of various constituents in crop residue varies from one plant species to another. Table 1 presents the chemical compositions of the four major crop residues and illustrates the annual productions in China. Among the major 4 crop residues, corn stover is the largest crop residue stream in China (327.4 million ton/year). Conversely, production of sugarcane bagasse is much lower in quantity than other three crop residues.

2.2. Bio-hydrogen production from the crop residues

Cellulose, hemicellulose, and lignin are main components of crop residues. Cellulose is a polysaccharide with β -1,4-glycosidic bonds. Crystalline cellulose is resistant to digest while amorphous

Table 1
Chemical compositions of four major crop residues and H₂ production potential in China.

Crop residue	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Production in China (million tones/yr)	References
Rice straw	32–47	19–27	5–24	195.1	Saratale et al. (2008) and Jiang et al. (2012)
Wheat straw	33–38	26–32	17–19	126.6	Saratale et al. (2008) and Jiang et al. (2012)
Corn stover	33,37.5	28,30	8.4	327.4	Zhang et al. (2014a), Jiang et al. (2012) and Li et al. (2009a)
Sugarcane bagasse	40–45	30–35	20–30	12.2	Rai et al. (2014) and Jiang et al. (2012)

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