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Hydrogen Production in Institute of Fluid Machinery of Polish Academy of Science in Gdańsk — theory and practice

Abstract
The hydrogen production technologies developed in the Institute of Fluid-Flow Machinery, Polish Academy of Sciences in Gdańsk are discussed here. They include the following methods: dark fermentation, photoelectrochemical water oxidation and hydrocarbons (or alcohols) reforming by microwave plasma. The potential of hydrogen production by using dark fermentation of different popular wastes such as: agricultural wastes, textile or wood waste, was determined using suitable models. Also, the influence of microaeration during dark fermentation of some substrates, e.g. sour cabbage, was tested. Photochemical oxidation is a water-splitting process driven by radiation at the surface of a titanium-oxide anode. The Si microrods covered by titania films were verified as a photoanode material. The hydrogen production from methane, ethanol, isopropanol and kerosene was driven by a microwave plasma. The results obtained confirm that microwave plasma sources have a high potential for hydrogen production via gaseous and liquid fuels reforming.

Keywords: hydrogen, dark fermentation, plasmolysis, photochemical water oxidation.

1. Introduction

Hydrogen is considered as the fuel of the future due to its high heat of combustion and its abundance (Biedron, 2015; Das, 2001; Sołowski, 2016a). Growing costs of energy and its demand in Poland brings with it increased involvement of research centers (among them Institute of Fluid-Flow Machinery, Polish Academy of Science in Gdansk — IMP PAN) in the development of renewable hydrogen-production technologies. Three methods of hydrogen production are developed in IMP PAN, including dark fermentation, microwave plasma assisted reforming and photochemical water oxidation. The dark fermentation research included theoretical analyses of recent data and modeling of hydrogen-source potential as well as experimental investigation of yields for various substrates (e.g. cotton or sour cabbage) and processes (e.g. the role of microaeration). The microwave plasma research (started in 2012) focused on efficiency of hydrogen production from ethanol, kerosene and isopropanol.

The research related to the photoelectrochemical water oxidation was established in 2016 in collaboration with the research group from Nanobiomedical Centre of Adam Mickiewicz University in Poznań. The undertaken efforts cover electrochemical and photoelectrochemical characterization of catalytic nanomaterials i.e. silicon nano- and micro-rods covered with different metal oxide films.

2. Dark Fermentation

Dark fermentation is a type of anaerobic digestion, which transforms simple organic compounds like glucose or glycerol into hydrogen, carbon dioxide, and organic acids. It proceeds using three possible pathways: acetate, butyrate or acetate-ethanol process (Bartacek et al., 2007; Woodward et al., 2000):

$$C_6H_{12}O_6 + 4H_2O \rightarrow 2CH_3COO^- + 2HCO_3^- + 2CO_2 + 4H_2 + 2H^+ \quad \Delta G^0 = -48 \text{ kJ mol}^{-1} \tag{1}$$

$$C_6H_{12}O_6 + 2H_2O \rightarrow CH_3CH_2CH_2COO + 2HCO_3^- + 2CO_2 + 2H_2 + 3H^+ \quad \Delta G^0 = -137 \text{ kJ mol}^{-1} \tag{2}$$

$$C_6H_{12}O_6 + 3H_2O \rightarrow CH_3COO^- + 2HCO_3^- + 2CH_3CH_2OH + 3H_2 \quad \Delta G^0 = -97 \text{ kJ mol}^{-1} \tag{3}$$

The hydrogen production by dark fermentation requires less energy than other methods and depends “only” on two variables: raw materials and bacteria (Sołowski, 2016a; 2018). The optimal condition for dark fermentation is widespread availability of raw material rich in carbohydrates (Toledo-Alarcón et al., 2017). According to Ren et al. (Ren et al., 2011; Wang et al., 2013; Liu et al., 2015) pure hexoses and pentoses are the most efficient raw materials for hydrogen production; high yields 124 g of H_2/g of glucose from wastes like used chewing gum (and 2l H_2 per litre of wastes) were confirmed by Seifert et al. (2018). Unfortunately substrates reach in simple sugars seldom occur in wastes, so it is necessary to use more widely available substrates such as lignocellulosic ones: e.g. corn wastes, wood wastes and herbivorous manure (Sołowski, 2016; Xing et al., 2010; Zhu et al., 2009).

The bacteria active in dark fermentation are divided into 2 groups: strict and facultative (Chaganti et al., 2012; Sołowski et al., 2018; Tommasi et al., 2008). Strict bacteria or obligate anaerobes (mostly *Clostridium*) are oxygen and substrate sensitive but produce hydrogen with high efficiency. Facultative bacteria like *Entereobacteria*, *Bacillus* or *Citrobacter* are less sensitive to oxygen or feed quality but at least 12% less efficient in hydrogen production than *Clostridium* (Batista et al., 2018). In order to produce hydrogen with high efficiency, the bacteria should be pretreated using thermal (heat shock), physical or chemical processes. These inhibit methanogenic processes that are consecutive to the hydrogen production stage of anaerobic digestion (Wang & Wan, 2008; Chaganti et al., 2012; Chasnyk et al., 2015). The stable continuous hydrogen production is hardly possible, so study results are related to batch type reactors or different types of CSTR (continuous stir tank reactors) (Ferraz et al., 2015; Keskin et al., 2018; Sołowski et al., 2018; Spasiano, 2018). The process can proceed under psychrophilic (below 30°C), mesophilic (33–38°C) or thermophilic conditions (above 55°C). The optimal pH value is in the range between 5 and 6 (Ghimire et al., 2015).

2.1. Model for calculation of hydrogen potential of the raw material

There are two lignocellulose-waste components desired for efficient dark fermentation, i.e. hemicellulose and cellulose, while lignin is considered as inhibiting of dark fermentation (Kongjan et al., 2010; Monlau et al., 2013; Toledo-Alarcón et al., 2017). The mass ratio of cellulose, hemicellulose and lignin vary for different kinds of plant, part of plant, age and area of occurrence. Thus for calculating of hydrogen potential a model was formed considering these lignocellulosic wastes and used to calculate the potential of some textile waste (cotton, flax) (Sołowski, 2016b), wood wastes (beech conifer, spruce, oak, pine) (Sołowski, 2016c) and cereal waste (for corn, wheat and barley) (Sołowski et al., 2019). From 1 kg of these wastes one can obtain potentially:
- 21 g of hydrogen from cotton waste,
- 19 g of hydrogen from linen waste,
- 16.9g of hydrogen for pine wood 1–20 years old,
- 17.4 g of hydrogen for pine wood 21–40 years old,
- 15.9g of hydrogen for pine wood 41–60 years old,
- 16.1g of hydrogen for pine wood 61–80 years old,
- 13.2 g of hydrogen for pine wood 81–100 years old,
- 16.6 g of hydrogen for spruce wood 41–60 years old,
- 11.8 g of hydrogen for fir wood 1–20 years old,
- 11.9 g of hydrogen for fir wood 21–40 years old,
- 12 g of hydrogen for fir wood 41–60 years old,
- 12.1g of hydrogen for fir wood 61–80 years old,
- 12.2 g of hydrogen for fir wood 81–100 years old,
- 17.5 g of hydrogen for beech wood 41–60 years old,
- 14.7 g of hydrogen for oak wood 1–20 years old,
- 14.8g of hydrogen for oak wood 21–40 years old,
- 15.6 g of hydrogen for oak wood 41–60 years old,
- 15.7 g of hydrogen for oak wood 61–80 years old,
- 16 g of hydrogen for oak wood 81–100 years old,
- 14.39 g of hydrogen from wheat straw,
- 13.86 g of hydrogen from wheat bran,
- 11.18 g of hydrogen from barley straw,
- 14.03 g of hydrogen from corn straw.

2.2. Role of microaerobic conditions

Influence of microaerobic conditions on dark fermentation of sour cabbage under neutral pH conditions, for VSS (volatile suspended solids) 5 g/l and 10 g/l was investigated (Sołowski et al., 2018a; Sołowski et al., 2018b). One of the known problems, which must be solved before viable process industrialization, is methane production inhibition (the process that consumes hydrogen). It is already known that hydrogen sulphur formation during anaerobic digestion can be prevented by the addition of small amounts of oxygen (Duangmanee 2009; Jenicek et al., 2010; Ramos et al., 2014). It was checked which process: methanogenesis or hydrogenesis, is more sensitive to small oxygen presence.

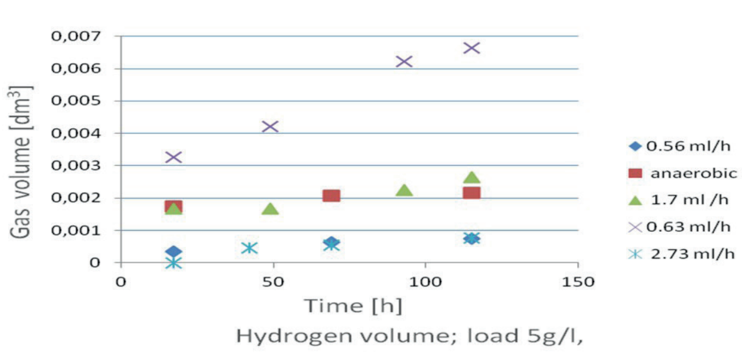

Fig. 1. Time evolution of total hydrogen production under strict anaerobic conditions (red squares) and with small oxygen flow rates: 0.56 ml/h (dark blue diamonds), 0.63 ml/h (violet crosses), 1.7 ml/h (green triangles), 2.73 ml/h (light-blue stars) (Sołowski et al., 2018; Sołowski et al., 2018b)

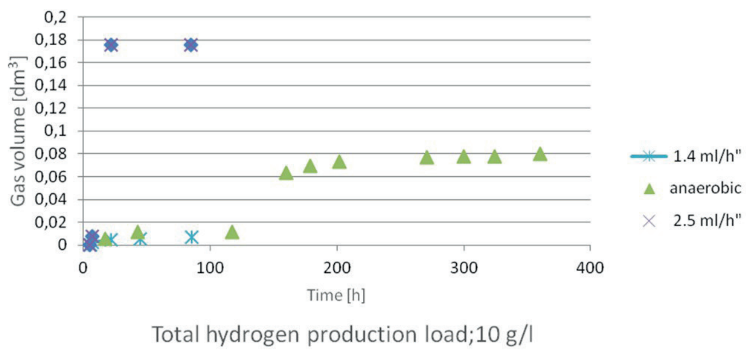

Fig. 2. Time evolution of total hydrogen production for load 10 g/l of sour cabbage under strict anaerobic conditions (green triangles) and with small oxygen flow rates: 2.5 ml/h (violet crosses), 1.4 ml/h (light-blue stars) (Sołowski et al., 2018; Sołowski et al., 2018a)

After 115 hours of dark fermentation, under strict anaerobic conditions and substrate load 5 g/l, methane production is twice as high and hydrogen production is 3 times as low compared with a system with oxygen flow rate 0.63 ml/h — see Fig. 1. The proper oxygen flow rate that can improve hydrogen production in the case of 5 g/l feed rate must be higher than 0.56 ml/h and lower than 1.7 ml/h.

For feed VSS 10 g/l the oxygen flow rate should be a minimum of 2.5 ml/h in order to increase hydrogen production. The highest hydrogen production was observed with an oxygen flow rate of 4.5 ml/h — see Fig. 2 (Sołowski et al., 2018a; 2018b).

3. Microwave plasma — based hydrogen production

The atmospheric-pressure microwave-plasma sources (MPS) suitable for hydrogen production from gaseous and liquid fuels offer significant advantages. Microwaves

(MW) supply the energy to create plasma in gases. Properly designed MPS assures high efficiency (almost 100%) of microwave power transfer from generator to the plasma. Thus MPS are considered to be more efficient in energy transfer than other plasma sources (i.e. dielectric barrier discharge, corona discharge or glow discharges). A MW plasma operated by electricity provides a fast response time of electrons, ionised and excited states of atoms, molecules and radicals of highly reactive properties. Due to this the catalyst-free processing of different hydrogen precursors becomes possible, at the same time avoiding the potential problems related to catalyst deactivation and regeneration. Additionally, thanks to the electrodeless operation of the MPS, a high purity plasma can be obtained.

Various atmospheric pressure MPS were designed, which supplied power through waveguides, coaxial lines or micro-strip lines, in IMP PAN (Mizeraczyk et al., 2012). However, for hydrogen production purposes a waveguide-supplied metal cylinder-based MPS (Jasiński et al., 2013) of different configuration and operated at two MW frequencies (915 MHz and 2.45 GHz) appeared to be the most convenient. The applied MPS configuration includes introducing the hydrogen precursor into the microwave plasma region either in the form of a swirl or axial flow, or directly into the MW-plasma flame, behind the MW-plasma generation-region. The decomposition of gaseous (methane, biomethane) and liquid hydrogen precursors (ethanol, isopropanol, kerosene) was performed. Figure 3 presents the idea of the microwave (915 MHz or 2.45 GHz) plasma system for hydrogen production from methane.

The influence of supplied microwave energy, of hydrogen precursor flow rate and of plasma forming gas flow rate on energy efficiency of hydrogen production (hydrogen production rate (g[H_2]/h), energy yield of hydrogen production (g[H_2]/kWh), conversion degree of the hydrogen precursor (%), hydrogen volume concentration in the outgas (%) and concentrations of other gaseous compounds resulting from the hydrogen precursor processing was investigated.

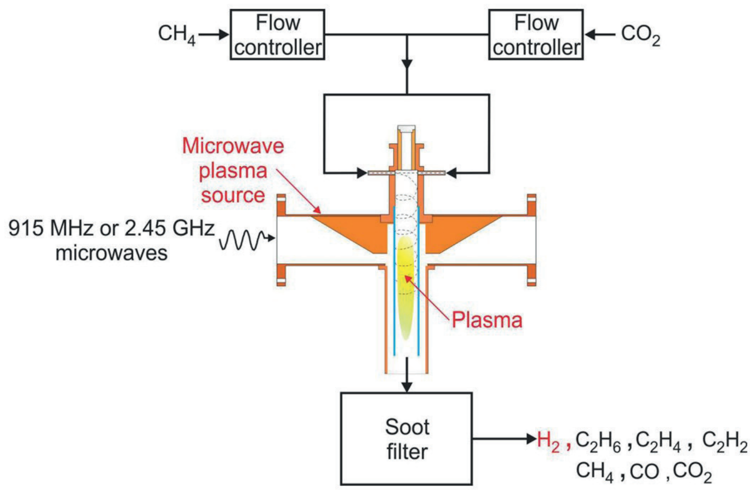

Fig. 3. Scheme of the microwave (915 MHz or 2.45 GHz) plasma system for hydrogen production from methane

Table 1. Comparison of hydrogen production rates and energy yields
for selected microwave plasma methods of hydrogen production

Initial gas composition (frequency)	Hydrogen production rate $g(H_2)/h$	Energy yield $g(H_2)/kWh$	Reference
CO_2 — 3000 NL/h CH_4 — 3000 NL/h (915 MHz)	**156** 108	21 **24**	Hrycak, Czylkowski, Jasiński, Dors, & Mizeraczyk, 2019
CO_2 — 1200 NL/h CH_4 — 3000 NL/h H_2O — 2 kg/h (2.45 GHz)	192	43	Czylkowski et al., 2016
N_2 — 3900 NL/h C_2H_5OH — 1.2 kg/h (915 MHz)	**96** 67	19 **22**	Miotk et al., 2016
CO_2 — 2700 NL/h C_3H_7OH — 2.4 kg/h (915 MHz)	93	18.5	Miotk et al., 2016
CO_2 — 2700 NL/h Kerosene — 1.2 kg/h (915 MHz)	37	7.5	Czylkowski et al., 2018

Table 1 presents a comparison of the best obtained hydrogen production efficiency parameters. It can be seen that the highest hydrogen yield was achieved in the case of combined steam reforming of methane.

4. Photochemical oxidation

The research in IMP PAM focused on verification of photochemical oxidation of different metal oxide layers loaded onto the silicon pillars acting as an ordered substrate. In the paper by Pavlenko et al. (2017), the influence of thickness of TiO_2 layer deposited over the Si pillars on their activity in solar driven water decomposition was studied. The voltage obtained for photolysis equals 1.16 V vs. RHE while usually water splitting process proceeds at 1.30 V (Grimes et al., 2008). The Si/TiO_2 exhibits weaker efficiency by 25% than WO_3, however this material is very much cheaper (Alexander et al., 2008; Bloor et al., 2016). The result is also better than reported by Ni et al. (2007). The highest current registered upon electrode illumination was achieved for material composed of 40 nm-thin titania film obtained via atomic layer deposition over the 5 µm-long Si pillars, see Fig. 4.

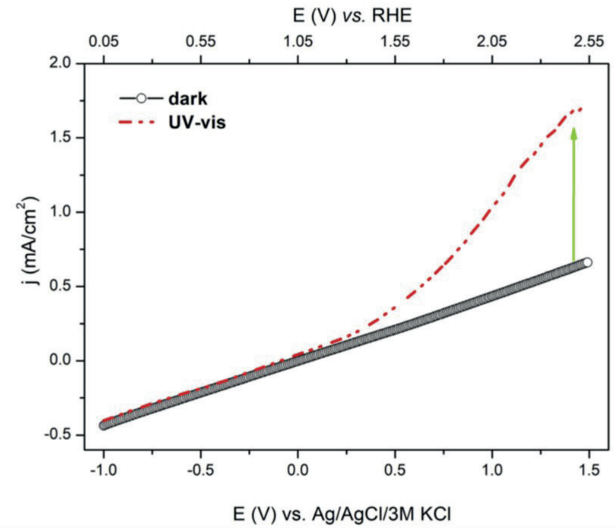

Fig. 4. Linear voltammetry curves of photocurrent density versus potential in TiO_2/SiNP for n-type Si. Length of SiNP equal to 5 µm; ALD TiO_2 thickness equals 40 nm; electrolyte solution was 0.5 M K_2SO_4 (Pavlenko et al., 2017)

5. Conclusions

Three technologies of hydrogen production, based on microwave plasmolysis, photochemical oxidation and dark fermentation, have been investigated in IMP PAN. A theoretical model has been developed to calculate potential of hydrogen production using the dark fermentation method from various substrates such as textile, wood and corn wastes. It was also proven experimentally that microaeration applied to anaerobic digestion of some substrates (like sour cabbage) inhibits methanogenesis and so, it supports hydrogenesis.

The experimental results of microwave-plasma investigation show that the hydrogen production efficiencies in the waveguide-supplied metal cylinder-based MW-plasma reactor of different configuration are acceptable. For example, the methane reforming (in mixture with CO_2 and H_2O) resulted in the energy yield of hydrogen production of 43 g/kWh, which is close to the U.S. Department of Energy (DOE) requirement (60 g/kWh by 2020) (see Randolph, 2013). Also, the absence of oxygen as by-products in the off-gas is highly beneficial. So, the proposed microwave plasma system is found to be a low cost and effective means of hydrogen production, and thus promising for industrial implementation.

Finally, it was found that the TiO_2 layer deposited over the Si pillars increase their activity in solar driven water decomposition.

References

Bartacek, J., Zabranska, J., Lens, P.N.L. (2007). Developments and constraints in fermentative hydrogen production. *Biofuels, Bioproducts and Biorefining, 1*, 201–214. Retrieved from: https://doi.org/10.1002/bbb.17.

Batista, A.P., Gouveia, L., & Marques, P.A.S.S. (2018). Fermentative hydrogen production from microalgal biomass by a single strain of bacterium Enterobacter aerogenes — Effect of operational conditions and fermentation kinetics. *Renewable Energy, 119*, 203–209. Retrieved from: https://doi.org/10.1016/j.renene.2017.12.017.

Biedroń, J. (2015). *Wodór — krwioobieg nowoczesnej rafinerii, a może paliwo przyszłości?* Gdańsk. Retrieved from: www.popihn.pl/download.php?id=199.

Bloor, L.G., Solarska, R., Bienkowski, K., Kulesza, P.J., Augustynski, J., Symes, M.D., Cronin, L. (2016). Solar-Driven Water Oxidation and Decoupled Hydrogen Production Mediated by an Electron-Coupled-Proton Buffer. *J. Am. Chem. Soc., 138*, 6707–6710. Retrieved from: http://doi.org/10.1021/jacs.6b03187.

Chaganti, S.R., Kim, D.H., & Lalman, J.A. (2012). Dark fermentative hydrogen production by mixed anaerobic cultures: Effect of inoculum treatment methods on hydrogen yield. *Renewable Energy, 48*, 117–121. Retrieved from: https://doi.org/10.1016/j.renene.2012.04.015.

Chasnyk, O., Sołowski, G., & Shkarupa, O. (2015). Historical, technical and economic aspects of biogas development: Case of Poland and Ukraine. *Renewable and Sustainable Energy Reviews, 52*, 227–239. Retrieved from: https://doi.org/10.1016/j.rser.2015.07.122.

Czylkowski, D., Hrycak, B., Miotk, R., Jasiński, M., Dors, M., & Mizeraczyk, J. (2018). Hydrogen-enriched gas production from kerosene using an atmospheric pressure microwave plasma system. *Fuel, 215*, 686–694. Retrieved from: https://doi.org/10.1016/j.fuel.2017.11.137.

Czylkowski, D., Hrycak, B., Miotk, R., Jasiński, M., Mizeraczyk, J., & Dors, M. (2016). Microwave plasma for hydrogen production from liquids. *Nukleonika, 61*(2), 185–190. Retrieved from: https://doi.org/10.1515/nuka-2016-0031.

Das, D. (2001). Hydrogen production by biological processes: a survey of literature. *International Journal of Hydrogen Energy, 26*(1), 13–28. Retrieved from: http://doi.org/10.1016/S0360-3199(00)00058-6.

Duangmanee, T. (2009). *Micro-aeration of hydrogen sulfide removal from biogas*. Iowa State University.

Ferraz Júnior, A.D.N., Etchebehere, C., & Zaiat, M. (2015). High organic loading rate on thermophilic hydrogen production and metagenomic study at an anaerobic packed-bed reactor treating a residual liquid stream of a Brazilian biorefinery. *Bioresource Technology, 186*, 81–88. Retrieved from: https://doi.org/10.1016/j.biortech.2015.03.035.

Ghimire, A., Frunzo, L., Pirozzi, F., Trably, E., Escudie, R., Lens, P.N.L., & Esposito, G. (2015). A review on dark fermentative biohydrogen production from organic biomass: Process parameters and use of by-products. *Applied Energy, 144*, 73–95. Retrieved from: https://doi.org/10.1016/j.apenergy.2015.01.045.

Grimes, C., Varghese, O., & Ranjan, S. (eds.). (2008). *Light, Water, Hydrogen: The Solar Generation of Hydrogen by Water Photoelectrolysis*. Boston (MA): Springer. Retrieved from: https://doi.org/10.1007/978-0-387-68238-9.

Hrycak, B., Czylkowski, D., Jasiński, M., Dors, M., & Mizeraczyk, J. (2019). Hydrogen Production via Synthetic Biogas Reforming in Atmospheric-Pressure Microwave (915 MHz) Plasma at High Gas-Flow Output. *Plasma Chemistry and Plasma Processing,* (0123456789). Retrieved from: https://doi.org/10.1007/s11090-019-09962-z.

Jasiński, M., Czylkowski, D., Hrycak, B., Dors, M., & Mizeraczyk, J. (2013). Atmospheric pressure microwave plasma source for hydrogen production. *International Journal of Hydrogen Energy, 38*(26), 11473–11483. Retrieved from: https://doi.org/10.1016/j.ijhydene.2013.05.105.

Jenicek, P., Koubova, J., Bindzar, J., & Zabranska, J. (2010). Advantages of anaerobic digestion of sludge in microaerobic conditions. *Water Science and Technology, 62*(2), 427–434. Retrieved from: https://doi.org/10.2166/wst.2010.305.

Keskin, T., Arslan, K., Nalakth Abubackar, H., Vural, C., Eroglu, D., Karaalp, D., Azbar, N. (2018). Determining the effect of trace elements on biohydrogen production from fruit and vegetable wastes. *International Journal of Hydrogen Energy, 43*(23), 10666–10677. Retrieved from: https://doi.org/10.1016/j.ijhydene.2018.01.028.

Kongjan, P., O-Thong, S., Kotay, M., Min, B., & Angelidaki, I. (2010). Biohydrogen production from wheat straw hydrolysate by dark fermentation using extreme thermophilic mixed culture. *Biotechnology and Bioengineering, 105*(5), 899–908. Retrieved from: https://doi.org/10.1002/bit.22616.

Liu, B.-F., Jin, Y.-R., Cui, Q.-F., Xie, G., Wu, J.-N., & Ren, N.-Q. (2015). Photo-fermentation hydrogen production by Rhodopseudomonas sp. nov. strain A7 isolated from the sludge in a bioreactor. *International Journal of Hydrogen Energy, 40*(28), 8661–8668. Retrieved from: https://doi.org/10.1016/j.ijhydene.2015.05.001.

Miotk, R., Hrycak, B., Czylkowski, D., Dors, M., Jasinski, M., & Mizeraczyk, J. (2016). Liquid fuel reforming using microwave plasma at atmospheric pressure. *Plasma Sources Science and Technology, 25*(3). Retrieved from: https://doi.org/10.1088/0963-0252/25/3/035022.

Mizeraczyk, J., Jasiński, M., Nowakowska, H., Dors, M. (2012). Studies of atmospheric-pressure microwave plasmas used for gas processing. *Nukleonika, 57*(2), 241–247.

Monlau, F., Aemig, Q., Trably, E., Hamelin, J., Steyer, J.P., & Carrere, H. (2013). Specific inhibition of biohydrogen-producing Clostridium sp. after dilute-acid pretreatment of sunflower stalks. *International Journal of Hydrogen Energy, 38*(28), 12273–12282. Retrieved from: https://doi.org/10.1016/j.ijhydene.2013.07.018.

Ni, M., Leung, M.K.H., Leung, D.Y.C., & Sumathy, K. (2007). A review and recent developments in photocatalytic water-splitting using TiO2 for hydrogen production. *Renewable and Sustainable Energy Reviews, 11*(3), 401–425. Retrieved from: https://doi.org/10.1016/j.rser.2005.01.009.

Pavlenko, M., Siuzdak, K., Coy, E., Jancelewicz, M., Jurga, S., & Iatsunskyi, I. (2017). Silicon/TiO2 core-shell nanopillar photoanodes for enhanced photoelectrochemical water oxidation. *International Journal of Hydrogen Energy, 42*(51), 30076–30085. Retrieved from: https://doi.org/10.1016/j.ijhydene.2017.10.033.

Ramos, I., Peña, M., & Fdz-Polanco, M. (2014). Where does the removal of HS from biogas occur in microaerobic reactors? *Bioresource Technology, 166*, 151–157. Retrieved from: https://doi.org/10.1016/j.biortech.2014.05.058.

Randolph, K. (2013). *Hydrogen Production. Annual Merit Review and Peer Evaluation Meeting.* Virginia: Arlington.

Ren, N., Guo, W., Liu, B., Cao, G., & Ding, J. (2011). Biological hydrogen production by dark fermentation: Challenges and prospects towards scaled-up production. *Current Opinion in Biotechnology, 22*(3), 365–370. Retrieved from: https://doi.org/10.1016/j.copbio.2011.04.022.

Seifert, K., Zagrodnik, R., Stodolny, M., & Łaniecki, M. (2018). Biohydrogen production from chewing gum manufacturing residue in a two-step process of dark fermentation and photofermentation. *Renewable Energy, 122*, 526–532. Retrieved from: https://doi.org/10.1016/j.renene.2018.01.105.

Sołowski, G. (2016). Obróbka lignocelulozy — pierwszy etap zielonej energii, chemii wraz z wodorem. In K. Szala, M. Kropiwniec (eds.), *Wybrane zagadnienia z zakresu ochrony środowiska i energii odnawialnej* (1st ed., pp. 56–75). Lublin: Fundacja Tygiel.

Sołowski, G. (2016a). *Alternatywne źródła energii — wybrane zagadnienia. Biohydrogen "the fuel of the future"; current methods of production and their comparison*. Retrieved from: http://bc.wydawnictwo-tygiel.pl/publikacja/8B19E6C9-44F9-68AE-01B0-D3D5DF6E9734.

Sołowski, G. (2016b). Theoretical potential of hydrogen production from textiles wastes in pomeranian region by means of dark fermentation. In T. Noch, W. Mikołajczewska, & A. Wesołowska (eds.), *Globalizacja a regionalna ochrona środowiska* (pp. 313–317). Gdańsk: Wydawnictwo Gdańskiej Szkoły Wyższej.

Sołowski, G. (2016c). Hydrogen production from wood waste by mean of dark fermentation. In K. Pikoń, & L. Czarnowska (eds.), *Contemporary Problems of Power Engineering* *and Environmental Protection 2016* (pp. 189–194). Gliwice: Published by Department of Technologies and Installations for Waste Management.

Sołowski, G. (2018). Bioprocessing and Biotechniques Biohydrogen Production — Sources and Methods: A Review. *International Journal of Bioprocessing and Biotechniques, 2018*(01), 1–22. Retrieved from: https://doi.org/10.20911/IJBBT-101.

Sołowski, G., Shalaby, M.S., Abdallah, H., Shaban, A.M., Cenian, A. (2018). Production of hydrogen from biomass and its separation using membrane technology. *Renewable and Sustainable Energy Reviews, 82*, 3152–3167. Retrieved from: https://doi.org/10.1016/j.rser.2017.10.027.

Sołowski, G., Hrycak, B., Czylkowski, D., Cenian, A., Pastuszak, K. (2018a). Oxygen sensitivity of hydrogenesis and methanogenesis. In *Contemporary Problems of Power Engineering and Environmental Protection 2017* (pp. 157–159).

Sołowski, G., Hrycak, B., Czylkowski, D., Cenian, A., Pastuszak, K., Konkol, I. (2018b). Hydrogen and methane production under conditions of dark fermentation process with low oxygen concentration. In T. Sabu (ed.), *Proceedings of the International Conference on Reuse and Recycling*. Kerala (India): Kottayam.

Sołowski, G., Konkol, I., Cenian, A. (2019). Theoretical potential of hydrogen production from corn wastes in Poland by means of dark fermentation. *Ecological Chemistry and Engineering S, 26*.

Spasiano, D. (2018). Dark fermentation process as pretreatment for a sustainable denaturation of asbestos containing wastes. *Journal of Hazardous Materials, 349*(February), 45–50. Retrieved from: http://doi.org/10.1016/j.jhazmat.2018.01.049.

Toledo-Alarcón, J., Capson-Tojo, G., Marone, A., Paillet, F. (2017). Basics of bio-hydrogen production by dark fermentation. In *Bioreactors for Microbial Biomass and Energy Conversion* (pp. 199–220).

Tommasi, T., Sassi, G., Ruggeri, B. (2008). Acid pre-treatment of sewage anaerobic sludge to increase hydrogen producing bacteria HPB: Effectiveness and reproducibility. *Water Science and Technology, 58*(8), 1623–1628. Retrieved from: https://doi.org/10.2166/wst.2008.506.

Wang, J.L., & Wan, W. (2008). Comparison of different pretreatment methods for enriching hydrogen-producing bacteria from digested sludge. *International Journal of Hydrogen Energy, 33*(12), 2934–2941. Retrieved from: https://doi.org/10.1016/j.ijhydene.2008.03.048.

Wang, B., Li, Y., Ren, N. (2013). Biohydrogen from molasses with ethanol-type fermentation: Effect of hydraulic retention time. *International Journal of Hydrogen Energy, 38*(11), 4361–4367. Retrieved from: https://doi.org/10.1016/j.ijhydene.2013.01.120.

Woodward, J., Orr, M., Cordray, K., Greenbaum, E. (2000). Enzymatic production of biohydrogen. *Nature, 405*, 1014–1015. Retrieved from: https://doi.org/10.1038/35016633.

Xing, Y., Li, Z., Fan, Y., Hou, H. (2010). Biohydrogen production from dairy manures with acidification pretreatment by anaerobic fermentation. *Environmental Science and Pollution Research, 17*(2), 392–399. Retrieved from: https://doi.org/10.1007/s11356-009-0187-4.

Zhu, J., Li, Y., Wu, X., Miller, C., Chen, P., Ruan, R. (2009). Swine manure fermentation for hydrogen production. *Bioresource Technology, 100*(22), 5472–5477. Retrieved from: https://doi.org/10.1016/j.biortech.2008.11.045.

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