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Hydrogen production via wastewater electrolysis – an integrated approach review

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Abstract. Human activities generate enormous amounts of wastewater. The hydrogen production from this new resource has gained attention as an emergent technology. Incorporating photovoltaic energy production with different electrolysis systems which can treat wastewaters and produce hydrogen simultaneously will lead to an environmentally-friendly and sustainable hydrogen production.

Keywords: Wastewater, Water, Electrolysis, Hydrogen, Renewable energy.

1 Introduction

Environmental concerns regarding the high demand for energy are one major issue, as human civilization is accompanied by an ever-growing need for energy. There is a global effort to reduce greenhouse gas (GHG) emissions associated with fossil fuels, as their use has a tremendous destructive environmental impact, such as climate change, ozone layer depletion, acidification, and air pollution [1, 2].

In the near future, most of the energy required for human activities should be provided by incident solar radiation instead of the air combustion of fossil hydrocarbons or nuclear reactions. This would prevent the deleterious impact of GHG emissions on the environment and would also bring some additional benefits such as the promotion of the energy independency of nations, a reduction in the competition for access to oil resources and could also contribute to solving the problems associated with the treatment and long-term storage of nuclear wastes, promoting an energy transition [3].

Implementing such an energy transition on a large scale and turning sunlight into renewable electricity needs an easy and affordable way to transport and store it. This

energy transition depends on the development of technical solutions for energy storage at different time and size scales. A universal chemical energy carrier which could be used for storage, transportation and distribution of renewable energy is required [3].

Gaseous hydrogen of electrolytic grade has been considered for many decades to be such a game-changing energy carrier. This is a by-product of brine electrolysis, but it can also be obtained in an efficient and affordable way through water electrolysis, while the Earth's atmosphere can be used as an oxygen reservoir of infinite capacity. Commercial water electrolysers are found in quite varied fields in industry, but so far the technology has been mainly used for stationary production in view of chemical applications. Regarding energy applications, existing plants of limited size are available only on a demonstration scale. Future water electrolysers will have to be customized to allow non-stationary modes of operation. Therefore, efforts are currently being made to develop hundred-MW scale systems [3].

In recent years, hydrogen has increasingly become an alternative energy carrier in the energy and automotive sectors, due to its renewable, transportable and emission-free properties [1, 4]. Moreover, by using fuel cells, hydrogen can be converted into electricity and operated continuously under hydrogen and oxygen. Unlike fossil fuels, hydrogen is not available freely in nature as a primary fuel. This means that it must first be produced from its sources such as natural gas or water, and then used as an energy source. Currently, reforming fossil fuels is the most common process used for commercial production of hydrogen, but this process has associated emissions of carbon dioxide (CO_2) and low efficiency. Therefore, there is great interest in developing alternative hydrogen production processes based on water-splitting (e.g. thermolysis, thermochemical, electrochemical, photochemical, photocatalytic and photoelectrochemical processes) which are environmentally friendlier and more sustainable. Taking the current environmental and energy issues into account, water electrolysis can be an efficient, clean and promising alternative technology for hydrogen production. This technique could be integrated well with the available renewable sources (such as solar, wind or hydropower). The major limitation of large-scale water electrolysis for mass production of hydrogen is the rather high overpotential required for the reactions. This overpotential plus the ohmic losses in the electrolysis process make the actual potential to exceed the standard 1.23 V potential of water electrolysis and reach values of around 1.8-2.0 V [4].

Most human and industrial activities lead to enormous wastewater generation. The majority of wastewater is routed for disposal in the environment without treatment, due to a lack of strict regulations in many developing countries. It causes a detrimental impact on human health, economic productivity, freshwater resource quality and the ecosystem. Sources of wastewater generated include domestic residence, commercial properties, industrial operations and agriculture. Hence, management of this wastewater is necessary with safe and effective collection methods. Treatment of wastewater and returning treated water back into the environment could have the least impact on the environment and ecosystem. Furthermore, wastewater is a valuable resource, which has more utility in generating cost-effective and valuable sustainable sources of energy, nutrients, organic matter, and other useful by-products.

2 Hydrogen production

Due to its highest gravimetric energy density, hydrogen has been regarded as the preferred clean-energy carrier, with potentially environmentally-friendly production through the solar-assisted splitting of water [5, 6].

Due to fluctuations in renewable energy production and consumption rates, "buffers" for energy storage, such as electrochemical energy conversion and storage systems (EECSs), are required. The most promising EECSs are redox flow cells, regenerative fuel cells, electrochemical conversion of CO_2 (and water or H_2) into fossil fuels (e.g. formic acid) and electrochemical capacitors. The annual consumption of hydrogen increases by 6% per year. Today, hydrogen is produced mainly from fossil fuels, mostly natural gas reforming and coal gasification [7], so these methods result in high CO_2 emissions, and efficiency is approximately 70-75% and 45-65% respectively. A small percentage of hydrogen (about 4%) is produced by water electrolysis, which consumes substantial energy (6-7 kWh per m^3 of hydrogen) [8].

Large amounts of pure hydrogen (99.999 vol%) can be produced using water electrolysis without emissions of gaseous pollutants. For these reasons, water electrolysis is considered today to be the most important hydrogen-production technology. The main research on hydrogen energy now focuses on the development of energy-efficient water electrolysis systems (electrode materials, electrolytes, separators, etc.) and effective H_2 storage methods required due to the low volumetric energy density of H_2 [7].

The water-splitting reactions (Eq. (1)) are endothermic and therefore require energy, which can be provided by an electric current through a suitable electrochemical cell.

$$H_2O + \text{energy} \rightarrow H_2 + \tfrac{1}{2} O_2 \tag{1}$$

Although it seems simple, the electrochemical splitting of water requires a detailed understanding of the anodic and cathodic mechanisms to achieve high rates and minimum electrical energy input needs.

The hydrogen evolution reaction (HER) exchange current of Pt is at least two orders of magnitude higher in acid than in alkaline electrolytes. On the other hand, the oxygen evolution reaction (OER), may occur through various pathways and adsorbed intermediates. RuO_2 and IrO_2, alone or in combination, are often considered the reference OER catalysts, but neither is "ideal". The reverse of the OER reaction is the oxygen reduction reaction (ORR), where molecular oxygen is reduced to water. ORR involves the same intermediates as the OER and is most conveniently carried out in an alkaline environment where catalysts which are more active and stable than in acid are available. Therefore, it remains a challenge to generate catalysts (beyond Pt, Ir and Ru) for both the HER and OER which can exhibit selectivity, remain stable over time, and can be produced using low-cost methods in large quantities. To reduce the cost of water electrolysis, substantial effort has been made to develop catalysts such as non-noble metals and non-metallic materials. Because high-activity Pt-based materials' low element abundance hinders their large-scale application, more cost-effective, earth-abundant catalysts with long-term stability are needed for the HER. To meet the demand, a variety of transition metal-based catalysts, including their corresponding single atomics, alloys,

nitrides, phosphides, carbides, selenides, sulphides, and tellurides, have been proposed. Examples are ternary metal phosphides (in particular, of Co and Mo) [5, 6, 9, 10, 11, 12, 13].

Water electrolysis could be carried out in different types of electrolytic systems such as alkaline electrolysers, PEM electrolysers, and the solid-oxide electrolysers (SOEs). However, using expensive materials (precious metals) in the fabrication of PEM or SOE electrolysers, along with their shorter lifetime, make them relatively more expensive compared to the alkaline cells for small-scale H_2 production systems. The current commercial alkaline water electrolysers mainly use aqueous solutions of sodium or potassium hydroxide as the state-of-the-art electrolyte. Although alkaline water electrolysis possesses an inherent low-cost characteristic, the development of large-scale hydrogen production systems based on this technology still needs potential improvements in the overall cell efficiency through reduction of the energy consumption and increase of the electrolyte ionic conductivity [4, 14, 15].

The “conventional” alkaline electrolysers typically operate with cell potentials near 2 V with a system efficiency near 60% and demonstrated lifetimes of more than 10 years. Commercial PEM electrolysers are available in smaller sizes than alkaline electrolysers with a lifetime of 5 or more years, where lifetime certainly would be a function of the operating temperature, resulting in increased efficiency but decreased durability when temperature rises. Furthermore, increased catalyst loading would cause the cost of the device to rise. Not only the price of the noble metals is high, but rather also system complexity, difficulties in scaling up, and the high cost of the membrane are the main disadvantages of PEM water electrolysers [9].

There is an incentive today to improve alkaline electrolysis over system scales larger than PEM electrolysis. This can be achieved in several ways: select better HER-OER catalysts; use system components and architectures which allow operation at high temperatures and reduce system complexity, capital, and operating costs; use an anion exchange membrane (AEM) in place of the electrolyte, resulting in a compact system, such as a PEM device and free of bubble effects, with a large choice of non-PGM catalysts, with low resistance and high stability [9].

3 Renewable energy sources

Contributions of fossil fuels (oil, coal and gas), hydropower, nuclear power and renewable resources (e.g. solar and wind) to global energy demand are approximately 86%, 6.8%, 4.43% and 2.77% respectively. Today, more than 70% of electrical energy is generated from fossil fuels. In fact, the burning of fossil fuels in recent decades has caused serious environmental problems with a huge impact on the climate change and global warming. Concerns about global CO_2 emissions and increasing costs of fossil fuels are motivating the development of technologies for energy production from renewable resources such as wind and solar energy [7].

Despite most Renewable Energy Systems (RESs) being known as "good" solutions to produce "green" energy, they require different structures which provide different energy costs and CO_2 emissions [16]. Therefore, it is necessary to identify the appropriate

structure for RESs to achieve energy sustainability. In the last decade, distributed energy resources (DERs) gained more attention and interest from governments because they are more "flexible" and have a low CO_2 emission. Photovoltaic (PV) systems are one of the most representative DERs, and are widely used in power generation [17, 18].

PV is expected to grow significantly as global energy transitions towards renewable energy, and by mid-century, PV systems will supply a large portion of the world's energy needs beyond the power sector as the result of new electricity-to-fuel technologies. Most of these technologies involve the production of renewable hydrogen from intermittent renewable electricity sources [19]. The production of H_2 based on an energy mix through a system using a mini-hydro plant (MHP) and a PV system was evaluated. The purpose of an MHP complementary to the PV system is to supply electrical energy to a water electrolyser, as the PV system is an intermittent power source and only works with sunlight, and the study has shown its technical and economic viability [19]. In addition, combined photovoltaic/thermal (PV/T) systems which simultaneously produce electricity and hot water can be considered in H_2 production, leading to higher electrical efficiency and an extended service life [20].

4 Wastewater electrolysis

Industrialization demands high water and energy consumption and generates large amounts of wastewater. The treatment of wastewater along with the generation of renewable energy resources is an ideal way of tackling these problems [1, 3].

Recently hydrogen production from wastewater has gained attention as an emergent technology. Hydrogen generation can be achieved by various methods, such as dark fermentation, photo fermentation, bio photolysis and microbial electrolysis. Using raw industrial wastewater for hydrogen production can be a high energy-intensive and low-yield process. This is because raw industrial wastewater consists of complex and recalcitrant biodegradable compounds which hinder the hydrogen yield and specific hydrogen production rate. Hence, to enhance the process's feasibility and sustainability, pre-treatment processes such as physical, chemical, biological and mechanical ones can be incorporated as an additional step. The pre-treatment process accelerates the hydrogen generation capacity of wastewater and enriches the hydrogen yield [1, 2].

Electrochemical methods are used to remove various organic and inorganic species of pollutants from wastewater. Using electrochemical methods for the treatment of organic effluents has some advantages compared with biological or chemical methods. In this context, water-treatment technologies based on electrochemical advanced oxidation processes (EAOPs) are more effective. This is due to the action of highly reactive oxygen species (ROS) such as hydroxyl radical *OH in the reaction mechanism, usually based on anodic oxidation (AO) or Fenton's reaction. Anodic oxidation combines high efficacy and simplicity, favouring the oxidative destruction of organics in waters through the direct action of *OH formed at the anode surface by oxidation of water via (Eq. (2)).

$$M + H_2O \rightarrow M(^*OH) + H^+ + e^- \tag{2}$$

In the anodic oxidation, the oxidation ability depends on the selected anode, and a wide variety of electrode materials have been investigated [3]. For example, dairy wastewater treatment was performed by electro-Fenton process [21]. Electrocoagulation was investigated for the treatment of agro-industry wastewaters [22], as well as swine manure effluents [23].

Electrochemical reactions, which can produce molecular hydrogen via water splitting, can degrade organic contaminants in water simultaneously, and the presence of wastewater organic matter can enhance hydrogen generation [24]. The electrooxidation of selected organic compounds was investigated to determine optimal process conditions towards the production of hydrogen from potential wastewater sources [25]. The photodegradation of organic wastewater and simultaneous hydrogen evolution was studied, using the photo-Fenton reaction [26, 27]. The HER in black liquor electrolysis was performed and it was concluded that it is kinetically more favourable than alkaline water electrolysis [28]. MoS_x was used as an electrocatalyst for HER in real acidic wastewaters [29]. Waste generated by the wine industry was also studied in a low-temperature PEM electrolysis cell [30]. Electro hydrolysis of landfill leachates was proven to be an effective method for hydrogen gas production with simultaneous COD removal [31], as well as olive mill wastewaters [32, 33], vinegar wastewaters [34], waste anaerobic sludges [35], domestic wastewaters [36, 37, 38], swine wastewaters [39], chicken industry wastewaters [40] and cheese whey wastewaters [27]. One different approach is to directly electrolyse biomass wastes [41, 42]. Hydrogen gas can also be produced from metal-plating wastewater by electro hydrolysis (or electro-coagulation process) [2].

5 Integration & related works

Integrating wastewater treatment and hydrogen production powered by RESs can be a way to improve the economy of green hydrogen. This approach is shown in Fig. 1.

There have been a few attempts to follow this integration path. At a lab scale, the direct treatment of wastewater generated in a textile plant by electrolysis powered by a photovoltaic system was evaluated. The results were promising for that kind of wastewater [43]. Similar experiments were carried out by evaluating the potential to produce H_2 through electrolysis of wastewater from ornamental-stone industries. The prototype of an electrolyser powered by a photovoltaic system was developed, which was shown to be effective in simultaneously producing H_2 and treat wastewater [44]. In another small-scale setup, experiments to produce H_2 by electrolysis powered by photovoltaic cells and using low-strength industrial wastewater were carried out [45, 46]. The “Greenlysis” project aimed to demonstrate the potential of producing H_2 via electrolysis of wastewater, powered by renewable electricity. In this approach, a PEM electrolyser and the treatment units of a wastewater treatment plant are powered by PV panels and wind turbines [47]. Experiments at a sub-pilot-scale for H_2 production from urban wastewater using electrolysis powered by a PV system were also carried out [48].

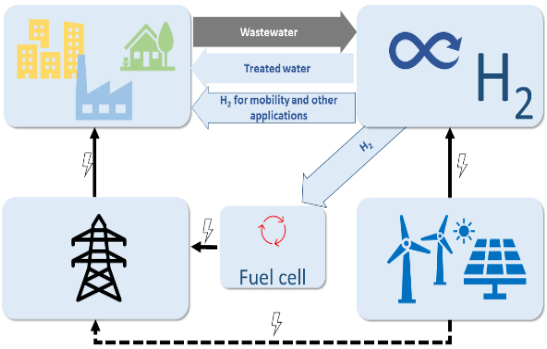

Fig. 1. Integration of hydrogen production with wastewater treatment, renewable energy sources and the electricity grid.

There are few examples in the literature close to the proposed integration approach, and the idea of using hydrogen to power the electrical grid is a new aspect in this area. This work is in its early stages. The authors are committed to pursuing it in the near future, using the PV system infrastructure already in place at the Polytechnic Institute of Tomar campus, aiming to study and test the viability of producing hydrogen from wastewater, by electrolysis powered by PV systems and using this hydrogen as fuel for different applications.

6 Conclusions

The integrated approach of hydrogen production through electrolysis of wastewater powered by renewable sources of electricity seems to have the potential to boost the hydrogen economy. The coupling of hydrogen production with wastewater treatment can contribute to simultaneously reducing the costs of wastewater treatment and the environmental impact of hydrogen production. Powering the electrolysis of wastewater with renewable sources of electricity can contribute to balancing the electricity grid and to the use of non-renewable sources, towards a full greener production of hydrogen.

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References

1. Sharmila, V. G., Banu, J. R., Kim, S.-H., Kumar, G.: A review on evaluation of applied pretreatment methods of wastewater towards sustainable H_2 generation energy efficiency analysis. International Journal of Hydrogen Energy 45 (15), 8329-8345 (2020).
2. Çokay, E., Gürler, Y.: Effects of metals in wastewater on hydrogen gas production using electrohydrolysis. International Journal of Hydrogen Energy 45, 3407-3413 (2020).
3. Klidi, N., Clematis, D., Delucchi, M., Gadri, A., Ammar, S., Panizza, M.: Applicability of electrochemical methods to paper mill wastewater for reuse. Anodic oxidation with BDD and $TiRuSnO_2$ anodes. Journal of Electroanalytical Chemistry 815, 16-23 (2018).
4. A. H., Bahman, Choolaei, M., Chaudhry, A., Qaalib, H.: A highly-efficient hydrogen generation electrolysis system using alkaline zinc hydroxide solution. International Journal of Hydrogen Energy 44 (1), 72-81 (2019).
5. Liu, M., Hof, F., Moro, M., Valenti, G., Paolucci, F., Pénicaud, A.: Carbon supported noble metal nanoparticles as efficient catalysts for electrochemical water-splitting. Nanoscale 12, 20165-20170 (2020).
6. Gong, L., Lan, K., Wang, X., Huang, X., Jiang, P., Wang, K., Yang, M., Ma, L., Li, R.: Carbon-coated Co-Mo-P nanosheets supported on carbon cloth as efficient electrocatalyst for Hydrogen Evolution Reaction. International Journal of Hydrogen Energy 45 (1), 544-552 (2020).
7. Amikam, G., Nativ, P., Gendel, Y.: Chlorine-free alkaline seawater electrolysis for hydrogen production. International Journal of Hydrogen Energy 43 (13), 6504-6514 (2018).
8. Chen, C., Bai, Q., Liu, J., Wang, Z., Cen, K.: Characteristics and anode reaction of organic wastewater-assisted coal electrolysis for hydrogen production. International Journal of Hydrogen Energy 45 (41), 20894-20903 (2020).
9. Marini, S., Salvi, P., Nelli, P., Pesenti, R., Villa, M., Berrettoni, M., Zangari, G., Kiros, Y.: Advanced alkaline water electrolysis. Electrochimica Acta 82, 384-391 (2012).
10. Huang, X., Xu, X., Luan, X., Cheng, D.: CoP nanowires coupled with CoMoP nanosheets as a highly efficient cooperative catalyst for hydrogen evolution reaction. Nano Energy 68, 104332 (2020).
11. Bhavanari, M., Lee, K.-R., Tseng, C.-J., Tang. I-H., Chen, H.-H.: CuFe electrocatalyst for hydrogen evolution reaction in alkaline electrolysis. International Journal of Hydrogen Energy (2021).
12. Zhao, T., Wang, Y., Karuturi, S., Catchpole, K., Zhang, Q., Zhao, C.: Design and operando/in situ characterization of precious-metal-free electrocatalysts for alkaline water splitting. Carbon Energy 2, 582–613 (2020).
13. Yao, N., Meng, R., Wu, F., Fan, Z., Cheng, G., Luo, W.: Oxygen-Vacancy-Induced CeO_2/Co_4N heterostructures toward enhanced pH-Universal hydrogen evolution reactions. Applied Catalysis B: Environmental 277, 119282 (2020).
14. Buttler, A., Spliethoff, H.: Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Renewable and Sustainable Energy Reviews 82, 2440–2454 (2018).
15. Grigoriev, S. A., Fateev, V. N., Bessarabov, D. G., Millet, P.: Current status, research trends, and challenges in water electrolysis science and technology. International Journal of Hydrogen Energy 45, 26036-26058 (2020).
16. Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., Gorini, R.: The role of renewable energy in the global energy transformation. Energy Strategy Reviews 24, 38–50 (2019).

17. Wu, Y., Lin, H.: Standards and guidelines for grid-connected photovoltaic generation systems: a review and comparison. IEEE Transactions on Industry Applications 53, 3205-3216 (2017).
18. Xu, D., Wang, G., Yan, W.: A novel adaptive command-filtered backstepping sliding mode control for PV grid-connected system with energy storage. Solar Energy 178, 222–230 (2019).
19. Pereira, C. A., Coelho, P. M., Fernandes, J. F., M.H. Gomes, M. H.: Study of an energy mix for the production of hydrogen, International Journal of Hydrogen Energy 42 (2), 1375-1382 (2017).
20. Cui, Y., Zhu, J., Zoras, S., Zhang, J.: Comprehensive review of the recent advances in PV/T system with loop-pipe configuration and nanofluid. Renewable and Sustainable Energy Reviews 135, 110254 (2021).
21. Davarnejad, R., Nikseresht, M.: Dairy wastewater treatment using an electrochemical method: Experimental and statistical study. Journal of Electroanalytical Chemistry 775, 364–373 (2016).
22. Drogui, P., Asselin, M., Brar, S. K., Benmoussa, H., Blais, J.-F.: Electrochemical removal of pollutants from agro-industry wastewaters. Separation and Purification Technology 61, 301–310 (2008).
23. Rahman, S., Borhan, M. S.: Electrolysis of swine manure effluents using three different electrodes Fe-Fe, Al-Al AND Fe-Al. American Journal of Agricultural and Biological Sciences 9 (4), 490-502 (2014).
24. Park, H., Choo, K.-H., Park, H.-S., Choi, J., Hoffmann, M. R.: Electrochemical oxidation and microfiltration of municipal wastewater with simultaneous hydrogen production: Influence of organic and particulate matter. Chemical Engineering Journal 215–216, 802–810 (2013).
25. Cheng, W., Singh, N., Maciá-Agulló, J. A., Stucky, G. D., McFarland, E. W., Baltrusaitis, J.: Optimal experimental conditions for hydrogen production using low voltage electrooxidation of organic wastewater feedstock. International Journal of Hydrogen Energy 37, 13304-13313 (2012).
26. Lin, Y.-T., Wang, Y.-H., Wu, J. C. S., Wang, X.: Photo-Fenton enhanced twin-reactor for simultaneously hydrogen separation and organic wastewater degradation. Applied Catalysis B: Environmental 281, 119517 (2021).
27. Kargi, F., Uzunçar, S.: Valorization of Cheese Whey by Electrohydrolysis for Hydrogen Gas Production and COD Removal. Waste and Biomass Valorization 4, 517–528 (2013).
28. Ghatak, H. R., Kumar, S., Kundu, P. P.: Electrode processes in black liquor electrolysis and their significance for hydrogen production. International Journal of Hydrogen Energy 33, 2904–2911 (2008).
29. Kokko, M., Bayerköhler, F., Erben, J., Zengerle, R., Kurz, P., Kerzenmacher, S.: Molybdenum sulphides on carbon supports as electrocatalysts for hydrogen evolution in acidic industrial wastewater. Applied Energy 190, 1221–1233 (2017).
30. Caravaca, A., Lucas-Consuegra, A. de, Calcerrada, A. B., Lobato, J., Valverde J. L., Dorado, F.: From biomass to pure hydrogen: Electrochemical reforming of bio-ethanol in a PEM electrolyser. Applied Catalysis B: Environmental 134–135, 302–309 (2013).
31. Kargi, F., Catalkaya, E. C.: Electrohydrolysis of landfill leachate organics for hydrogen gas production and COD removal. International Journal of Hydrogen Energy 36, 8252-8260 (2011).
32. Kargi, F., Catalkay, E. C.: Hydrogen gas production from olive mill wastewater by electrohydrolysis with simultaneous COD removal. International Journal of Hydrogen Energy 36. 3457-3464 (2011).

33. Oz, N. A., Eker, A. C. U.: Simultaneous hydrogen production and pollutant removal from olive mill wastewaters using electrohydrolysis process. Chemosphere 232, 296-303 (2019).
34. Kargi, F., Arikan, S.: Hydrogen gas production from vinegar fermentation wastewater by electro-hydrolysis: Effects of initial COD content. International Journal of Hydrogen Energy 38, 2701-2708 (2013).
35. Kargi, F., Catalkaya, E. C., Uzuncar, S.: Hydrogen gas production from waste anaerobic sludge by electrohydrolysis: Effects of applied DC voltage. International Journal of Hydrogen Energy 36, 2049-2056 (2011).
36. Yarımtepe, C. C., Türen, B., Oz, N. A.: Hydrogen production from municipal wastewaters via electrohydrolysis process. Chemosphere 231, 168-172 (2019).
37. Cho, K., Hoffmann, M. R.: Molecular hydrogen production from wastewater electrolysis cell with multi-junction BiO_x/TiO_2 anode and stainless steel cathode: Current and energy efficiency. Applied Catalysis B: Environmental 202, 671–682 (2017).
38. Sharma, L., Prabhakar, S., Tiwari, V., Dhar, A., Halder, A.: Optimization of EC parameters using Fe and Al electrodes for hydrogen production and wastewater treatment. Environmental Advances 3, 100029 (2021).
39. Lourinho, G., Brito, P. S. D.: Electrolytic Treatment of Swine Wastewater: Recent Progress and Challenges. Waste and Biomass Valorization 12, 553–576 (2021).
40. Thirugnanasambandham, K., Sivakumar, V., Maran, J. P.: Optimization of process parameters in electrocoagulation treating chicken industry wastewater to recover hydrogen gas with pollutant reduction. Renewable Energy 80, 101-108 (2015).
41. Hibino, T., Kobayashi, K., Ito, M., Nagao, M., Fukui, M., Teranishi, S.: Direct electrolysis of waste newspaper for sustainable hydrogen production: an oxygen-functionalized porous carbon anode. Applied Catalysis B: Environmental 231, 191–199 (2018).
42. Yang, L., Liu, W., Zhang, Z., Du., X., Gong, J., Dong, L., Denga, Y.: Hydrogen Evolution from Native Biomass with Fe^{3+}/Fe^{2+} Redox Couple Catalyzed Electrolysis. Electrochimica Acta 246, 1163–1173 (2017).
43. Pathak, A. K., Kothari, R., Tyagi, V. V., Anand, S.: Integrated approach for textile industry wastewater for efficient hydrogen production and treatment through solar PV electrolysis. International Journal of Hydrogen Energy 45, 25768-25782 (2020).
44. Marques, F. C., Silva, J. C. M., Libardi, C. P., de Carvalho, R. R., Sequine, G. F., Valane, G.M.: Hydrogen production by photovoltaic-electrolysis using aqueous waste from ornamental stones industries. Renewable Energy 152, 1266-1273 (2020).
45. Kargi, F.: Comparison of different electrodes in hydrogen gas production from electrohydrolysis of wastewater organics using photovoltaic cells (PVC). International Journal of Hydrogen Energy 36, 3450-3456 (2011).
46. Eker, S., Kargi, F.: Hydrogen gas production from electrohydrolysis of industrial wastewater organics by using photovoltaic cells (PVC). International Journal of Hydrogen Energy 35, 12761-12766 (2010).
47. Marzo, E., Gali, A., Lefevre, B., Bouchy, L., Vidal, A., Cortina, J. L., Fabre, A., Hydrogen and Oxygen Production using Wastewater Effluent Treated with Ultra-Filtration and Membrane Distillation (Greenlysis). Procedia Engineering 44, 1744-1746 (2012).
48. Choi J., Ou H.-H., Soong S.H., Park H., Choo K.-H., Hoffmann M.R., Sub-pilot-scale hybrid electrochemical system for hydrogen production and wastewater treatment using solar panel, ACS National Meeting Book of Abstracts, 2011 241st ACS National Meeting and Exposition, Anaheim, CA, 27 March 2011 - 31 March 2011.