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Biological production of hydrogen from food waste treatment

Yung-Tse Hung [1,*], London Voss [1], Howard H. Paul [2] and Christopher R. Huhnke [1]

[1] *Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, Ohio, USA.*
[2] *Department of Information Systems, Cleveland State University, Cleveland, Ohio, USA.*

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Abstract

The improper conduct of food waste creates a global problem if nothing is remediated. Hydrogen's potential ability to be converted from food waste creates an appealing possibility as a renewable energy option. The environmental search for renewable energy sources is ever present in the age of rapid fossil fuel consumption. Hydrogen as a renewable source of energy is considered to be the most efficient and clean. Recent lab studies provide a promising outlook on this environmental accomplishment through the processes of dark fermentation and anaerobic digestion. This paper will highlight the current and emerging processes that aim to solve major global environmental concerns.

Keywords: Bio-Hydrogen; Food Waste; Dark Fermentation; Renewable energy

1. Introduction

Human civilization relies on the energy resources that provide means of transportation, manufacturing, illumination, and many other things necessary for life to exist as it has. Generally speaking, the field of energy resources aims to create energy from natural resources. The route of these resources, however, are often nonrenewable resources and their abundance finite on this planet. The depletion of nonrenewable energy resources is a problem that environmentalists have acted to slow down and remediate since its discovery.

Energy will always be needed to sustain human life, there is no avoiding that. It is not sustainable nor realistic to prevent humankind's tendency to exploit the environment for financial gain. The solution must come with technology that provides benefits for the environment and feasible for industries to comply. While much research has been done to remediate this problem with varying levels of success, a solution that is keen to the observer is one that remediates two environmental problems in one. The need for nonrenewable energy resources matches the need for reducing industrial waste.

1.1. Food Waste Data

Food loss and waste is food that is not eaten. The causes of food waste or loss are numerous and occur throughout the food system, during production, processing, distribution, retail and food service sales, and consumption. Overall, about one-third of the world's food is thrown away. A 2021 meta-analysis that did not include food lost during production, by the United Nations Environment Program found that food waste was a challenge in all countries at all levels of economic development. The analysis estimated that global food waste was 931 million tons of food waste (about 121 kg per capita) across three sectors: 61 per cent from households, 26 per cent from food service and 13 per cent from retail (1).

* Corresponding author: Yung-Tse Hung

1.2. Fossil Fuel Source

The two most common sources for hydrogen production are fossil fuels and biomass. Fossil fuels “A large variety of fossil fuels, such as natural gas, oil, and coal, can be applied to produce hydrogen via steam reforming or partial oxidation. The increasing demand for hydrogen, together with the growing coal chemical industry, deterioration of crude oil, upgrading of fuel oil quality, and progress in hydrogen energy technologies, has resulted in benefits and challenges for small- and large-scale coal-to-hydrogen production. Thereafter, hydrogen is recovered by pressure swing adsorption (PSA), which has the advantages of wide adaptability of feeding gas, cleanliness, energy saving, a high degree of automation, good reliability and flexibility, convenient startup and shutdown, high hydrogen purity, etc. The future directions for this technique are as follows:

- Improving the performance of the adsorbent,
- Optimizing the adsorption tower structure to strengthen the utilization rate of the adsorbent and eliminate the influence of pressure and temperatures on the stability, and
- Separating the gas mixture by coupling the low-temperature absorption and membrane technology.

Additionally, it is very important to study high-efficiency catalysts (e.g., iron-based oxides) for the water-gas shift reaction” (2). While hydrogen’s chemical existence may seem simple in context, understanding its complexities is crucial for this research.

2. Hydrogen production processes

“Unlike fossil fuels, hydrogen is not readily available in nature. It can be however produced from any primary energy source and to be then used as the fuel either for direct combustion in an internal combustion engine or in a fuel cell, only producing water as a byproduct” (3). This benefits over most production processes that tend to create more waste than product and is an additional incentive for the process. “As the only carbon-free and possessing the highest energy content compared to any known fuel, as shown in table 1, hydrogen is globally accepted as an environmentally benign secondary form of renewable energy, alternative to fossil fuels. A further advantage is that, supported by appropriate storage technologies, hydrogen can be utilized for domestic consumption as it can be safely transported through conventional means, and in order to be fed to stationary fuel cells, it can be stored as compressed gas, cryogenic liquid, or solid hydride. Currently the annual production of hydrogen is about 0.1 GT which is mainly consumed on-site, in refining and treating metals. A small fraction is already used to fuel driving cars while in the near future applications including power generation and heating in residential and industrial sectors are expected” (3).

2.1. Production From Fossil Fuels

As discussed before, the primary distinction between energy sources is renewable capability. While hydrogen can be produced from fossil fuels, this still creates an issue of nonrenewable source. It is still important to understand the distinction of “There are several technologies of producing hydrogen from fossil fuels, the main of which are hydrocarbon reforming and pyrolysis. These methods are the most developed and commonly used, meeting almost the entire hydrogen demand. Specifically, up to date hydrogen was produced 48% from natural gas, 30% from heavy oils and naphtha, and 18% from coal. Presently, fossil fuels retain their dominant role in the world hydrogen supply as the production costs are strongly correlated to fuel prices which are still kept to acceptable levels.

2.2. Current State Of Industrialization

The current state of biological hydrogen production “According to public reports, the total global demand for hydrogen has rapidly increased from 255.3 billion cubic meters in 2013 to 324.8 billion cubic meters in 2020, an increase of 27.2%. From the previous analysis, it is clear that hydrogen, as a secondary energy source, should be extracted from substances, such as hydrocarbons and water, through an energy conversion process, such as thermochemistry and water electrolysis. Among them, thermochemical processes using fossil as raw materials are particularly used in many industries, mainly including steam reforming of hydrocarbons, partial oxidation of heavy oil, coal gasification, and water electrolysis.

3. Hydrogen production processes

Oftentimes in production, the byproducts are the factors environmentalists consider most heavily in its impact to the world. “Presently, the utilization of fossil fuels are causing global climate change mainly due to the emission of pollutants like CO_x, NO_x, SO_x, C_xH_x, soot, ash, droplets of tars and other organic compounds, which are released into the atmosphere as a result of their combustion. In order to remedy the depletion of fossil fuels and their environmental misdeeds hydrogen has been suggested as the energy carrier of the future. It is not a primary energy source, but rather serves as a medium through which primary energy sources (such as nuclear and/or solar energy) can be stored, transmitted and utilized to fulfill our energy needs. Hydrogen is the most plentiful element in the universe, making up about three-quarters of all the matter" (4).

3.1. Photosynthesis and Biophotolysis

Photosynthesis is defined as the process by which green plants and some other organisms use sunlight to synthesize foods from carbon dioxide and water. Photosynthesis in plants generally involves the green pigment chlorophyll and generates oxygen as a byproduct. Bio photolysis is the production of hydrogen from water by sunlight energy using biological systems. Photoautotrophic organisms such as microalgae and cyanobacteria are capable of oxygenic photosynthesis. (5). "Photoautotrophic microorganisms, either prokaryotic cyanobacteria or eukaryotic green microalgae, possess chlorophyll and other pigments to capture sunlight energy and use photosynthetic systems (PSII and PSI) to carry out plant-like oxygenic photosynthesis. The pigments in PSII, P680, absorb the photons with a wavelength shorter than 680 nm, generating a strong oxidant capable of splitting water into protons, H+,, electrons e- and O2. The electrons or reducing equivalents are transferred through a series of electron carriers and cytochrome complex to PSI. The excess reduced carbon is stored inside the cells as carbohydrates (CH2O) and/or lipids" (6). The current state of environmental pollution is reason enough to be concerned with the rapid growth of industrial waste so this increased focus on these productions of clean energy alternatives could have ramifications that change the environmental outlook globally.

"This method uses the same processes found in plants and algal photosynthesis but adapts them for the generation of hydrogen gas instead of carbon- containing biomass. Photosynthesis involves the absorption of light by two distinct photosynthetic systems operating in series: a water splitting and O2 evolving system (''photosystem II" or PSII) and a second photosystem (PSI), which generates the reductant used for CO2 reduction. In this coupled process, two photons (one per photosystem) are used for each electron removed from water and used in CO2 reduction or H2 formation. In green plants only CO2 reduction takes place, as the enzymes that catalyze hydrogen formation, the hydrogenases, are absent. Microalgae, both eukaryotic (such as the green algae) and procaryotes (the cyanobacteria or blue–green algae), have hydrogenase enzymes, and can produce hydrogen under certain conditions" (5). The variety of sources of hydrogen production from a variety of algae and microbial organisms provides insight into the benefits and disadvantages of multiple organisms. Many studies have been conducted specifying one type of organism that creates precise specifications in this line of work.

3.2. Dark Fermentation

Dark fermentation is the fermentative conversion of organic substrate to biohydrogen. It involves a series of biochemical reactions using three steps that can be compared to anaerobic conversion that involves a diverse group of bacteria. It is a complex process manifested by diverse groups of bacteria, involving a series of biochemical reactions using three steps similar to anaerobic conversion. Dark fermentation differs from photo fermentation in that it proceeds without the presence of light. "Dark fermentative hydrogen production is an effective and feasible technology for biological hydrogen production. The inhibitory concentration and mechanism were discussed in-depth and comprehensively. The strategies for mitigating these inhibitory factors were also introduced and discussed. Suggestion for future study in this aspect was proposed to promote the scale-up and commercial application of dark fermentative hydrogen production" (7). This paper will discuss the studies conducted and compile a variety of publications and their importance and implications to the future use of the widespread use of this technology.

The importance of the process of dark fermentation is important and has an increased focus in the environmental community due to its advantages over other processes. "Hydrogen production through biolysis is clean and requires low energy input. The biohydrogen production processes include dark fermentation, photo fermentation, direct and indirect bio photolysis, Among them, dark fermentative hydrogen production is thought to be a more effective and feasible method, because it can use organic wastes as substrate, which can achieve dual aims to treat the wastes and produce clean energy simultaneously. Dark fermentative hydrogen production refers to the process of degrading organic substances by anaerobic bacteria to produce hydrogen, and the environmental condition should be anaerobic and dark. Various hydrogen-producing microorganisms have been isolated, characterized and applied for the fermentative hydrogen production" (7). Because dark fermentation offers an alternative unmatched by others, the studies conducted showed much more promising results.

3.3. Anaerobic Digestion

The process of anaerobic digestion works in the absence of oxygen to break down biodegradable material with microorganisms. Its use in waste and wastewater treatment is vast and spans back several years so its processes are familiar in the environmental community. Its use in the process of biological hydrogen production provides another method that could allow for this outcome and the solutions desired among many. “Food waste and sewage sludge are the most abundant and problematic organic solid wastes in Korea. The generation of food waste reaches about per day, accounting for 23% of municipal solid wastes. It is the major source of odor emanation, vermin attraction, toxic gas emission and groundwater contamination in collection, transportation and landfill of solid wastes due to the high organic concentration (volatile solids/total solids: 0.8–0.9) and moisture content (75–85%)” (8).

4. Renewable energy

The struggle for an energy source that will create a sustainable future for the increasingly industrialized societies. “We are witnessing changes in all energy sectors. Strong decarbonization and fossilization is necessary to realize the set climate targets by 2050. An example of these challenges is the “European Green Deal'', a strategy that aims to transform the European Union (EU) into a society with no net greenhouse gas emissions in 2050. This is where renewable energy sources (RES) play a leading role. Within this framework of energy transition, hydrogen was identified as an important energy carrier for coupling the transportation, heating and electricity sectors. Hydrogen can be produced from water in an electrolyze using electric energy coming from different RES, such as solar or wind. This can be applied in residential and industrial sectors. In recent years, a lot of research was conducted in the field of hydrogen storage. One possible way of storing hydrogen is using salt caverns, as they proved to be an excellent reserve system for crude oil and natural gas. The main goal of storing hydrogen in underground salt caverns is to compensate for seasonal fluctuations in electrical energy, which increase the reliability of the future energy systems, which mostly rely on the RES” (9).

4.1. Alternative Renewable Energy Resources

While the technology and laboratory and practical results of biological hydrogen production as a source of renewable energy have been promising, the end goal is clear to reduce carbon emissions and provide a sustainable alternative. Any process that achieves those objectives has their advantages and drawbacks and have been analyzed under an increased amount of pressure in recent years. An overview of other potential renewable energy sources will be discussed to follow in order to compare to the biological hydrogen production. “The subject of renewable energy (RE) concerns experts as well as the general public increasingly. Studies on renewable energy sources (RES) have increased in the last years in absolute and relative terms. RES can perform an important role by addressing the issues of fossil fuel depletion and global warming. Fossil fuels, nuclear resources, and renewable resources are the three main sources of energy. RES such as solar, wind, biomass, geothermal, and hydropower are utilized to reproduce energy and are therefore extensively useful to combat energy crises. A recent study of communities in Western Greece focused on the public attitude and the willingness to pay for electricity from renewable electricity sources.

4.2. Current And Emerging Applications

Because of the increased focus and pressure to create a long term and sustainable solution, there have been some current applications of renewable energy sources with varying degrees of success. “As stated by the U.S. Energy Information Administration renewable energy sources regenerate, unlike fossil fuels, which are finite. According to, there are five renewable energy sources in the world which are commonly used: biofuels which include biomass (wood and waste), ethanol, and biodiesel; hydropower; geothermal; wind; and solar. Biomass is one of the most important renewable energy sources used in the United States. The transportation and applications of H_2 are related to each other and many efforts were done and needed to expand for better handling of this promising technology in near future (10).

5. Bio-hydrogen limitations and future perspectives

While the studies and research have shown promising results in using food waste to biologically produce hydrogen as a renewable energy source, it is evident that it is not currently done as a mainstream energy source. It is important to understand why there are reservations on the adoption of these processes and why all environmental change tends to take such a long time, which in turn wastes valuable time that the globe may not have. However, there is some validity in the concerns that affect the logistics of these processes and can also create costs and feasibility issues that create a certain threshold of production. In a world where profits and production are prioritized over almost anything, there is still room for many improvements in these areas in order to gain more attraction and widespread adoption across the globe.

5.1. Hydrogen Storage and Transportation

The logistics of environmental solutions often set them back because they tend to be a large change that conflicts with the current processes. “Large scale industry usage policy of hydrogen requires good package, storage and transportation from the production site to the users. Hence, research needs to be done to ensure that the material for H2 storage is safe, reliable and cost-effective” (10).

“Hydrogen storage is known as a challenging topic. The materials used cannot have a strong interaction with hydrogen or any reaction. Besides, traditional storage techniques with a high pressure gas cylinders (compressed hydrogen) and liquid hydrogen; the physisorption of H2 on materials with essential parameters such as a high specific surface area, hydrogen intercalation in metals and complex hydrides, thereby the storage of H2 based on metals are being reviewed.

6. Food waste solutions

“Discharge of waste in general, and food waste, in particular, is considered one of the major environmental problems today, as waste generation increases continuously, reaching values of 32% of all food produced worldwide. There are many different options that can be applied to the management and evaluation of waste treatment, and Anaerobic Digestion seems to be one of the most suitable solutions because of its benefits, including renewable energy generation in the form of biogas. Moreover, if FW (food waste) is digested in anaerobic digesters from Wastewater Treatment Plants, a common solution is provided for both residues. Furthermore, co-digestion of food waste and sewage sludge provides benefits in terms of anaerobic process stability enhancing the buffer capacity of ammonia, for example, and biogas formation, which can be increased up to 80% when compared with mono digestion. The present paper reviews food waste anaerobic digestion from its generation, characteristics and different options for its management, and it does focus specifically on the anaerobic digestion and co-digestion process, stages, limiting rates and parameters, utilizing numerous experiences, strictly related to food waste. Pre-treatments are also considered as they are important and innovative for enhancing biogas production and its methane yield. The paper shows an extensive collection of pre-treatments, its basics, improving factors, and numerical data of biogas formation improvements that are related both to substrate modification and to the synergistic effect of co-digestion, which could lead to an increase of methane production from 11% to 180%” (11). The following figure shows the hierarchy of control that can be used as solutions for the problem at hand. This illustrates the ranking of effectiveness of control measures currently in place for solving the food waste problem.

The solution for food waste must occur the most with prevention. While this initiative proves difficult considering it requires every person to engage and participate in an environmental action that is difficult to see the effects of in a lifetime, due to the fact that if it works, it will seem like the countermeasure was unnecessary.

6.1. Anaerobic Digestion of Food State

Anaerobic digestion of food waste is suitable due to the characteristics described. “AD study and applications have been growing in the last decades, for many reasons, especially its suitability to treat any kind of biodegradable residue like FW or municipal waste, and the needs for renewable energy generation and other waste destinations that are different from landfilling. FW is perfectly suitable for AD because of its composition and moisture content. In general, terms, carbohydrates and proteins are traduced in a common biogas yield with faster transformation. On the contrary, lipids present a slower biodegradability development, but they provide a higher level and quality of biogas. Therefore, it is important to understand the mechanism of the AD process and all of the reactions involved” (11).

7. Case studies

The best way to learn specifics about a process is to understand the specific studies and applications. Below will be discussed specific studies that work with food waste to biologically produce hydrogen as a source of renewable energy. This process has promising results and is still being improved today in order to gain a more mainstream use. These case studies will be broken down into the objective, methods and materials, and then the results and discussions drawn and pulled together to overview the state of the process and the realities of its uses in today's climate.

7.1. Promising Lab Results

‘The current work evaluated the performance of one and two stage mesophilic fermentation, in continuous stirred tank reactors (CSTR), of food waste based on biogas yield and production rate, and overall energy recovery. Microbial seed was obtained from a full-scale up flow anaerobic sludge blanket (UASB) reactor treating cassava wastewater. Coarse matter >0.5 mm diameter was removed by sieving and the granules were washed twice with tap water. The fine granules used in the hydrogen fermentation were boiled at 100 °C for 30 min to deactivate methanogens, while those without heat treatment were used in methane production stage" (12).

"In this study, the experimental results of biohydrogen production from food waste operated for 10 days indicated that maximum hydrogen yield of 44.83 mL H2/g COD add was obtained at optimal conditions of initial pH 8.0, initial F/M ratio 4.0 and iron concentration 100 mg FeSO4/L under thermophilic condition. Moreover, major VFA productions of acetate (324.69 mg/L) and butyrate (765.66 mg/L) were observed in the reactor and B/A ratio was about 2.36. The COD removal efficiency was detected at 66.00%. Therefore, suitable operating conditions of fermentation from organic waste can be considered as the key factors for enhancing biohydrogen production from food waste" (13). This offers a promising outlook and also offers which conditions affect the most optimal system for production.

8. Conclusion

Food waste is considered any food, in any part of the food production process, that is not eaten and wasted. It is estimated that about a third of the world's food is wasted, causing a myriad of issues. This proposes issues with environmental and agricultural climate changes, as well as the logistic issues that threaten the cleanliness and conditions of where the food is dumped. This is a major environmental problem across the globe that also creates an unnecessary amount of land and water resources that are used in the production that are wasted if the food is not eaten.

Perhaps an even more vital environmental problem that poses the globe is the need for a reliable and realistic renewable energy source. Fossil fuels are currently used as the majority of the source of energy for the world that relies on it for nearly everything from manufacturing transportation, technologies, communications and more. While the wide use of nonrenewable energy sources poses problems for the sustainability of the industrialized world, it also creates carbon emissions that are harmful to the earth's atmosphere and create even more environmental issues.

The way that these two environmental concerns are related brings to light an environmental solution that could change the world. Using food waste as a source of biological hydrogen production to use as a source of renewable energy is an interesting and compelling process with increased amounts of focus over the last decade due to the increased need for a renewable energy source. Hydrogen is especially attractive as a source of ocean energy because of its versatility and ability to be produced from a variety of sources. Recent studies have shown that this process is possible and continuously shows promising results that could provide clean energy for the future. The improvements made in recent years show promising results and will continue to improve with the increased amounts of pressure to determine a feasible solution.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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