Recent Trends in Hydrogen Storage Using Agricultural Waste

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Abstract

Hydrogen is becoming popular as a clean energy source in the wake of the depletion of fossil fuels and the unhealthy climate. It burns cleanly and produces only water, which removes greenhouse gaseous emissions. However, challenges such as productive, economical, and safe storage hinder hydrogen use. The study is about innovations in hydrogen storage that use agricultural waste and focuses on production methods such as biomass gasification and biological processes. Biomass gasification, especially steam versus air gasification, has a great influence on hydrogen yields and economic viability, while dark fermentation and photofermentation convert organic matter into hydrogen. However, both processes face challenges in yield and efficiency problems, requiring optimisation for effective implementation.

Without a doubt, hydrogen storage technology is the backbone of a hydrogen economy. Each storage method has its own unique pros and cons. Compressed gas storage is usually density combined with the requirement for expensive tanks in which to place it; by contrast, liquid hydrogen is efficient, but boil-off losses are a problem. Solid-state storage, using such materials as metal hydrides, is the compact option but especially slow in terms of hydrogen absorption compared to the other methods above. Adsorption-based storage, using activated carbon or MOFs, is generally lower capacity; however, it is the most economical. Environmental impact, economic feasibility, and life cycle assessments (LCAs) must weigh in evaluating agriculture manures for bio-hydrogen. Future research should be devoted to developing biomass conversion processes, storage materials, and favourable policies for bio-hydrogen commercialisation.

Keywords: Hydrogen, gasification, life cycle assessments

1. INTRODUCTION

Hydrogen as an energy source is being thrust ever more upon us at the present time because of the global energy crisis, characterised by fossils being drained and climatic considerations rising in intensity [1]; [2]. Hydrogen, being widely available and clean upon combustion, presents itself as a suitable clean energy carrier [3]; [4]. The combustion of hydrogen, in contrast to other fossil fuels, only liberates water as an end product; hence, promisingly reducing the emission of greenhouse gases [1]. However, there are quite a number of prominent challenges facing the widespread application of hydrogen. Efficient production methods in a cost-effective manner are very much crucial, as one comes across technologies with rather low conversion efficiency and high production costs [3]; [5]. Safe and scalable storage technologies are yet another necessity since hydrogen, having a low volumetric energy density at ambient conditions, is very difficult to store [6]. These hurdles are a space for innovations, of which the use of agricultural wastes as an environmentally friendly feedstock would provide a very convincing route into a more sustainable hydrogen economy [4]; [7]. The main aim of this research paper is to review recent trends in hydrogen gas storage based on agricultural waste, including various production technologies and storage technologies with economic and environmental implications.

2. A thermochemical process for biomass gasification

This is biomass partial combustion, an operation that uses gasifying agents (usually steam, air, or oxygen) at a temperature of 800 to 1000°C. Gasification is inclusive of pyrolysis, steam gasification, and air gasification. Each energises up some extent, disbenefits, and availabilities. Steam gasification uses steam as the gasifying agent with a strong concentration of hydrogen and carbon monoxide in its produced syngas. Air gasification, in turn, uses air as a gasifying agent and produces syngas along with an inferior quantity of hydrogen but consumes less energy for the entire activity. The suitable gasification process will depend on the agricultural waste type, the specifications of the syngas desired, and the resources which are available. A comparison shows that while steam gasification generally produces a higher yield of hydrogen, it is, however, less energy efficient than air gasification. Both methods, however, yield syngas, which is further purified in a separation process to recover hydrogen from other components such as carbon monoxide, carbon dioxide, and methane; this purification process bears a heavy weight of overall hydrogen production cost and efficiency.

Various agricultural wastes are suitable feedstocks for gasification, including rice husk, corn stover, sugarcane bagasse, and oil palm empty fruit bunches [4]; [11]; [12]. The choice of feedstock influences the syngas composition and the overall economics of the process. For instance, oil palm waste, abundant in palm oil-producing regions like Malaysia [4], presents a readily available and cost-effective feedstock. The economic and environmental viability of biomass gasification depends on various factors, including feedstock costs, gasification technology, energy consumption, and carbon emissions [13]; [2]. Life cycle assessments (LCA) are crucial for evaluating the overall environmental impact, considering factors such as greenhouse gas emissions, land use change, and waste management [14]. Studies have shown that biomass gasification can significantly reduce greenhouse gas emissions compared to fossil fuel-based hydrogen production, but optimisation is essential to minimise environmental impact [2].

3. Dark and Photo-Fermentation

Dark fermentation, as understood here, is anaerobic digestion of organic matter without light [7]; [2]. Several species of bacteria, such as Clostridium, ferment carbohydrates to hydrogen, volatile fatty acids, carbon dioxide, and other products [15]. Photofermentation is, conversely, the ability to harness light as an energy source for hydrogen production by photosynthetic microorganisms such as cyanobacteria and purple non-sulphur bacteria [2]; [15]. Photofermentation typically uses the by-products of dark fermentation (e.g., volatile fatty acids). Therefore, dark versus photo-fermentation is a comparative analysis to reveal the benefits and disadvantages of both methods. The dark fermentation process does work on broader substrate frameworks, while photofermentation achieves higher hydrogen productivity rates with light input as the energy source [15]; [7].

These can be complemented by two types of agricultural waste: household waste and agricultural waste [7]. Pretreatment of the wastes may be needed for decreasing the fermentation efficiency, and the pretreatment option will depend on the waste type and microbial community involved [12]; [16]. Things like low hydrogen production yield, slow reaction rates, and the need for efficient separation of hydrogen from other gases are challenges faced by biological hydrogen production [7]; [15]. Optimising fermentation conditions (pH, temperature, substrate concentration) would form the other key area to maximise hydrogen production [7]; [4].

4. Hydrogen Storage

Materials and Technologies Efficient hydrogen storage is required for the future development of an economy based on hydrogen energy. Each existing technology has its benefits and negative aspects. For example, compressed gas in high-pressure tanks (350-700 bar) allows storing hydrogen in pressure storage at a high energy density per unit volume, needing strong, expensive and of course safe tanks under such high pressures [18]. Liquid hydrogen storage blends the liquid form of hydrogen while keeping it at cryogenic temperatures (-253°C), leading to volumetric energy density exceeding that of compressed gases [6]; [17]. This is significantly challenged due to boil-off losses resulting from heat leakage, which in turn requires high insulation and energy costs from refrigeration methods. 18. Storage of hydrogen in solid-state could indeed present a safer and more compact alternative. Solids are materials that can absorb and release hydrogen reversibly through reactions and processes like these [19]; [5]; [17]. Examples of such materials are metal hydrides such as magnesium hydride (MgH_2) [20]; [21], promising candidates because of their capacity for extensive storage of hydrogen. But the materials in most cases suffer from slow kinetics of absorption/desorption and higher temperatures of operation [19].

Adsorption-based storage uses porous materials, such as activated carbon, metal-organic frameworks (MOFs), and zeolites, to adsorb hydrogen onto their surfaces [5]; [22]. Activated carbon derived from agricultural waste is particularly active due to its low cost, abundant availability, and tunable properties [23]; [24]. However, the hydrogen storage capacity of adsorption-based methods is generally lower than that of compressed gas or liquid hydrogen storage at ambient temperatures [5]. The selection of an appropriate hydrogen storage method depends on the specific application, considering the factors such as energy density, safety, cost and operating conditions [5]; [6] and [7].

5. Economic and Environmental Considerations

The economic feasibility and environmental impact of hydrogen storage using agricultural waste are critical factors determining its widespread adoption. Life Cycle Assessments [LCAs] are essential tools for evaluating the overall environmental footprint of bio-hydrogen production, considering all stages from feedstock cultivation to hydrogen storage and utilisation [13]; [2]. LCAs can compare bio-hydrogen with traditional hydrogen production methods (e.g., steam methane reforming) to assess relative greenhouse gas emissions, energy consumption, and land use [25]; [26]. Studies have shown that bio-hydrogen production can significantly reduce greenhouse gas emissions compared to fossil fuel-based methods, but the extent of reduction depends on various factors, including the type of agricultural waste, gasification/fermentation technology, and energy efficiency [27]. Economic analysis is crucial for determining the cost-effectiveness of bio-hydrogen production and storage. Factors such as feedstock costs, processing costs, storage costs, and transportation costs influence the overall cost of bio-hydrogen [13]; [2]. The cost competitiveness of bio-hydrogen compared to traditional hydrogen production methods depends on several factors, including government policies, carbon pricing mechanisms, and technological advancements [26]; [28]. Policy incentives, such as carbon credits and subsidies, can play a crucial role in making bio-hydrogen economically viable [13]; [28]. Furthermore, the social and economic benefits of utilising agricultural waste, such as improved waste management, job creation, and enhanced rural development, should be considered [12]; [29]; [6].

6. Future Research Directions and Conclusion

This review highlights the significant potential of agricultural waste for sustainable hydrogen production and storage. While several promising technologies exist, further research and development are necessary to overcome the existing challenges and enhance the overall efficiency, cost-effectiveness, and scalability of biohydrogen systems [3]; [4]; [7]. Key research areas include improving the efficiency of biomass gasification and fermentation processes [5], developing advanced hydrogen storage materials with high capacity and fast kinetics [6], and optimising the integration of production and storage technologies [28]. Furthermore, research focusing on cost reduction strategies, including the development of low-cost catalysts and improved process designs, is crucial for making bio-hydrogen competitive with traditional hydrogen production methods [21]. Policy support is essential for promoting the widespread adoption of bio-hydrogen. Government policies and incentives, including carbon pricing mechanisms, subsidies, and renewable energy standards, can encourage investment in bio-hydrogen technologies and accelerate their commercialisation [13]; [28]; [30]. International collaboration is also crucial for sharing knowledge, promoting technological advancements, and establishing standardised protocols for bio-hydrogen production and storage [12]. In conclusion, utilising agricultural waste for hydrogen production and storage presents a promising pathway towards a more sustainable energy future. Addressing the remaining challenges through continued research and development, coupled with supportive policies, will be critical for realising the full potential of bio-hydrogen as a clean and sustainable energy carrier [1] – [3].

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