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Life Cycle Assessment of 1 kg Hydrogen Production Utilizing Dry Reforming of Biogas Produced via Anaerobic Co-digestion of Biomass [†]

Khan Mohammad Naim Abdullah [1], Md. Rakib Hasan Roni [1,*] and Swarna Saha [1]

[1] Department of Chemical Engineering, Bangladesh University of Engineering and Technology; 1602050@che.buet.ac.bd (K.M.N.A.); sahaswarna02023@gmail.com (S.S.)
* Correspondence: 1602054@che.buet.ac.bd; Tel.: +8801623111082

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Abstract: The energy demand is experiencing an upward trajectory, primarily driven by the utilization of fossil fuel resources. However, due to fuel shortage, rising demand, and environmental concerns, people are seeking green alternatives. Hydrogen fuel is a clean, efficient, and renewable option. This research investigates the synthesis of hydrogen via the dry reforming process of biogas produced through the anaerobic co-digestion method. It also addresses the study of life cycle assessment of both renewable and non-renewable hydrogen production routes. A life cycle assessment has been performed using 1 kg of hydrogen generation as the functional unit. A cradle-to-gate analysis has been considered for this study. A definitive boundary system has been considered from biomass generation to 1 kg H_2 production. The system boundary includes the building of several units, catalysts, biomass and water transportation, cooling water supply, heat, and electricity distribution, etc. For the entire procedure, a well-calculated inventory has been established. The evaluation of environmental footprints has been performed using the software openLCA. Five impact categories (climate change, ozone depletion, acidification, particulate matter formation, and freshwater eutrophication) were investigated and compared to both a renewable and a non-renewable method from a previous investigation. The effectiveness of implementing anaerobic co-digestion for producing H_2 through dry reforming process over conventional coal gasification and renewable electrolysis is described and demonstrated by graphs. This study reveals that anaerobic co-digestion is preferable to energy-intensive electrolysis and coal gasification, despite its considerable freshwater eutrophication.

Keywords: hydrogen production; anaerobic co-digestion; life cycle assessment; environmental impact

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1. Introduction

In recent years, there has been a significant increase in interest in the production of hydrogen as a renewable energy carrier and storage medium, as well as its prospective application as a substitute for fossil-based fuels [1,2]. The growing concern about greenhouse gas (GHG) emissions has focused attention on the pressing need to develop sustainable, clean, and highly efficient hydrogen production pathways [3]. Bangladesh, with its promising biomass and solar energy supplies, must harness these resources effectively. To maximize their potential for energy or hydrogen generation, we can look to the vast quantities of daily food waste, which, despite its higher moisture content, can be efficiently converted into biogas and hydrogen through anaerobic digestion [4].

There are various methods for producing hydrogen, including photo fermentation, steam methane reforming (SMR), fast pyrolysis, gasification, photo electrolysis, thermolysis, etc. However, biomass-based pathways, such as anaerobic co-digestion and dry reforming of biogas, are gaining attention due to their potential to generate hydrogen while simultaneously managing organic waste and reducing greenhouse gas emissions.

Life Cycle Assessment (LCA) is an extensive approach used to examine a product, process, or service's environmental impacts throughout its life cycle. This includes raw material extraction, manufacturing, use, and disposal [5,6]. Antonio Valente et al. (2015) compiled 509 original case studies in a global overview of hydrogen energy systems. Europe leads with 59% of studies, followed by North America (29%), and China emerging as a significant contributor in Asia [7]. Notable studies include Hailin Tian et al. (2020), who assessed the sustainability of industrial technologies like incineration and anaerobic digestion, favoring the latter for environmental benefits [8].

The dry reforming (DRM) reaction, which is the focus of this study, is an endothermic reaction between methane and carbon dioxide that produces a mixture of carbon monoxide and hydrogen, known as syngas [9]. Szabolcs Szima (2019) highlighted that dry methane reforming represents a pioneering approach to hydrogen production, wherein CO_2 is utilized in the reforming process. In this process, CO_2 capture rate can be as high as 90% [10].

$$CH_4 + CO_2 \leftrightharpoons 2CO + 2H_2, \Delta H^\circ(25^\circ C) = +247.4 \text{ kJ/mol}$$

This paper introduces a unique addition to the field of hydrogen production by focusing on a particular and inventive method: the use of dry reforming of biogas produced through anaerobic co-digestion of biomass for hydrogen generation. A full life cycle assessment is used to provide insights and recommendations for enhancing the environmental efficiency of hydrogen production by dry reforming. The developing biohydrogen sector may benefit from the results of this research.

2. Methodology

This study evaluates the environmental implications of co-anaerobic digestion-produced hydrogen using a Life Cycle Assessment (LCA). The life cycle assessment (LCA) technique was followed according to ISO 14040 and ISO 14044, international standards. The process includes aim and scope definition, life cycle inventory analysis, impact assessment, and interpretation.

2.1. Goal and Scope Definition

This life cycle assessment (LCA) study presents the environmental consequences of dry reforming biogas from anaerobic co-digestion of biomass in Bangladesh to produce hydrogen. The functional unit and system boundaries have been determined in this study. The production of 1 kg of hydrogen at the plant entrance is the functional unit for this study. This study covers the complete product life cycle, from raw material extraction to hydrogen production. It excludes hydrogen purification, improvement, and distribution. Digestate sludge processing was also kept out of our scope for this study. The system boundary considered for this study is demonstrated in Figure 1.

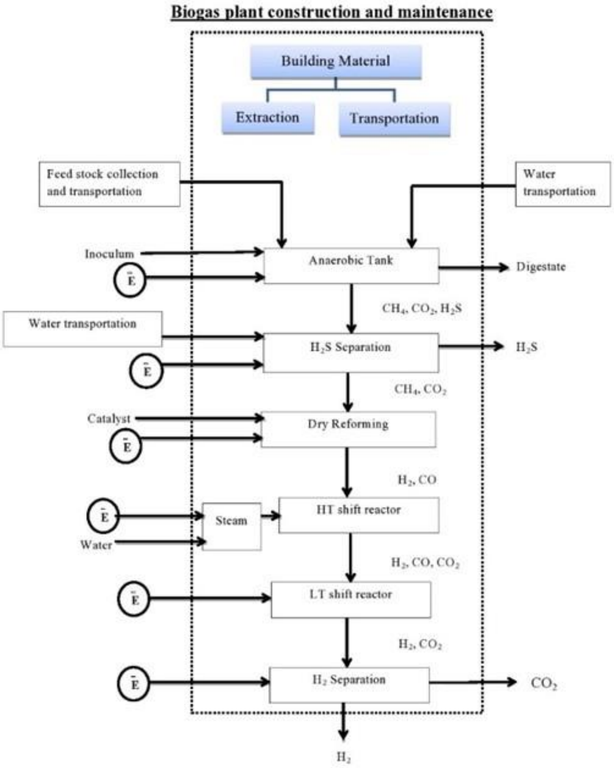

Figure 1. The system boundary of evaluated anaerobic co-digestion pathway to producing H_2.

2.2. Life Cycle Inventory Analysis

In this research on hydrogen synthesis from biomass, a two-step procedure was explored. The first is the anaerobic co-digestion of poultry droppings and wheat straw, which produces methane-rich biogas (60% CH_4, 39% CO_2) and digestate (which is kept out of consideration in our system boundary). Secondly, the dry reformation of biogas to produce hydrogen was carried on by passing it through high and low-temperature shift reactions and separating H_2 as a product using the pressure swing adsorption process. In the anaerobic fermentation process, microorganisms hydrolyze and ferment polymers and monomers of biomass to produce carbon dioxide and methane [11]. Taking into account the humid weather conditions of Bangladesh, a previously worked out experimental result of 70:30 of poultry droppings (PD) and wheat straw (WS) having higher moisture content has been taken into consideration for this study which produced 330 NL of methane per kg volatile solid when kept under a mesophilic temperature of 35 ± 1 °C for 90 days [12]. The digester construction inventory was based on data obtained from a community-based biogas plant in Bogra, Bangladesh. 22.619 kg biomass combination in a 70:30 PD: WS ratio was used to generate 5.182 NL of biogas in a 60:40 ratio of CH_4 & CO_2 which requires 1 digester unit of 100 m^3 capacity. At this stage, methane-rich biogas was produced with ppm levels of H_2S, which might cause catalyst deactivation in subsequent stages. As a result, the separation of this toxic gas is prioritized first by utilizing a ferric oxide bed to absorb H_2S while biogas passes through the bed and 4.43 ppm of H_2S is separated [13]. Following that, methane and carbon dioxide were dry-reformed using a Ni bed catalyst. The kinetic data acquired for similar ratios of CH_4 and CO_2 are used to determine the construction material and catalyst requirements through a MATLAB model [14,15]. A HYSYS model was developed to simulate the whole process starting from dry reforming to PSA separation to recycling of excess CO_2. The endothermic dry reformer ((1 atm, 800 ºC) model was simulated as a Gibbs reactor [16]. Output stream from the dry reformer was passed through a high-temperature shift reactor (27 bar, 350–450 ºC) where steam was injected and then moved into a low-temperature shit reactor (1 atm, 220 ºC), where Fe_3O_4/Cr_2O_3 and $CuO/ZnO/Al_2O_3$ was used as catalyst respectively. The kinetic model data required to build these two units, as well as to calculate the material of construction and the catalyst requirement, were collected from a previous experimental investigation [17]. As per the simulation, the end product of the LTS reactor contains only H_2O, H_2, and CO_2. To separate the H_2 end product adsorption bed of silica and activated carbon was used to adsorb H_2O and CO_2 [18]. Carbon dioxide was separated and recycled back to the dry reformer, where it was mixed with fresh clean biogas (without H_2S). The overall plant operating period was considered as 20 years having the capacity of 1000 kg/h hydrogen production. A detailed inventory analysis including the construction, transportation, and operating phases of this study is presented in Table S1.

3. Result and Discussion

3.1. Impact Assessment

Life Cycle Impact Assessment for this study was performed using software openLCA version 1.10.3 and considering ReCiPe Midpoint (E) as the impact assessment method. For this research specifically, 5 impact categories were studied. Climate change (GWP500) was found to be the most impactful category of amount 14.63 kg CO_2-Eq/kg H_2 where most of the emissions occurred from the Pressure Swing Adsorber (PSA) unit (65%). Freshwater eutrophication (FEP) was found to be 0.084 kg P-Eq/kg H_2. The Anaerobic Digestion Plant unit for biogas production was found as the most contributing unit for this impact category (97.5%). Ozone depletion (ODP) was measured as 7.49×10-7 kg CFC-11-Eq/kg H_2. Besides particulate matter formation (PMFP) and terrestrial acidification (TAP500) were found as 0.023 kg PM_{10}-Eq/kg H_2 and 0.096 kg SO_2-Eq/kg H_2. The percentage contributions of different process units for those five impact categories have been shown in Figure 2**.**

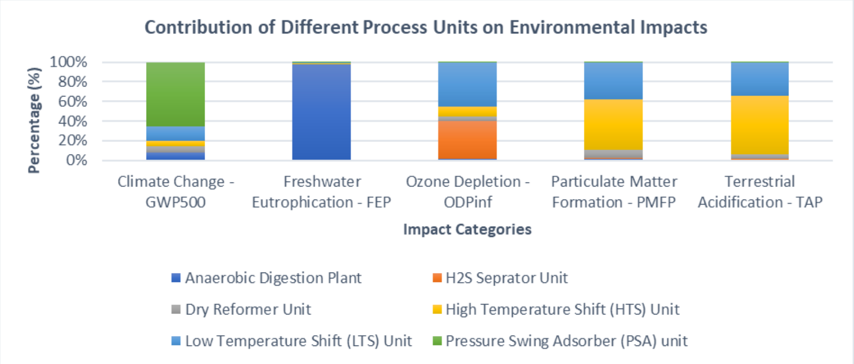

Figure 2. Contributions of 5 midpoint impact categories for different process units.

3.2. Interpretation

This study has taken into account the impact category GWP500, which refers to a 500-year time horizon for calculating global warming potential (GWP), potentially to capture longer-term impacts of greenhouse gas emissions. Hydrogen production from dry reforming of biogas produced by co-digestion of poultry droppings and wheat straw has the best Global Warming Potential (GWP) result of the three analyzed hydrogen production pathways as shown in Figure 3(a). One of the renewable routes, Electrolytic hydrogen production using proton exchange membrane fuel cell (PEM) with grid electricity has a GWP of 29.54 kg CO_2-Eq/kg H_2. GWP for fossil-based H_2 generation from coal gasification was 24.2 kg CO_2-Eq./kg H_2, approximately double that of our studied process [6]. However, it was more environmentally friendly than PEM electrolytic hydrogen production in this effect area.

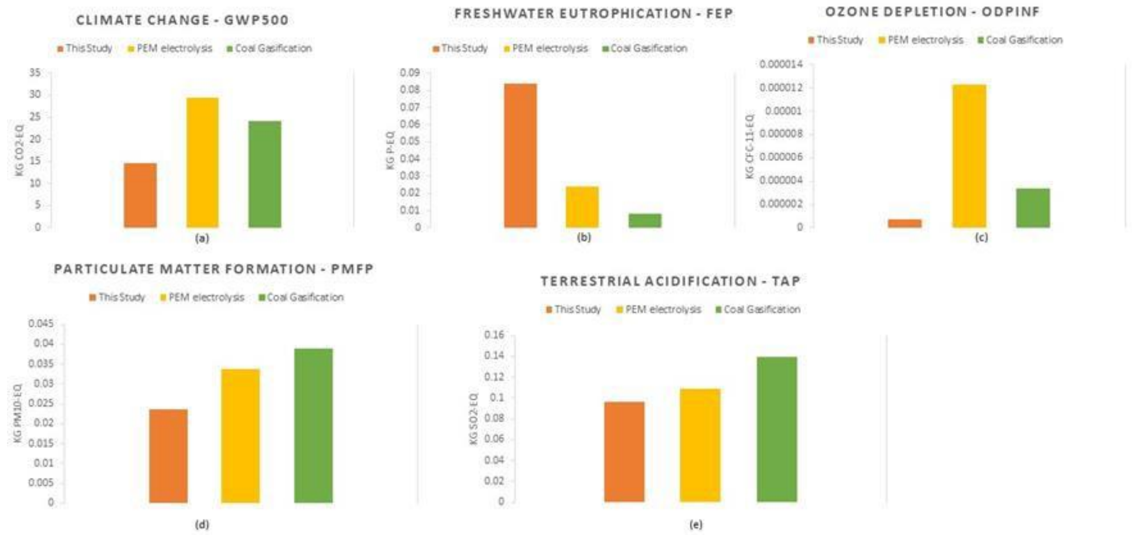

Figure 3. Comparative analysis of Environmental impact results of different pathways of Hydrogen production with this study: (**a**) Climate Change - GWP500 (**b**) Freshwater Eutrophication – FEP (**c**) Ozone Depletion – ODPinf (**d**) Particulate Matter Formation – PMFP (**e**) Terrestrial Acidification – TAP.

Hydrogen production through our studied process was found to have the lowest score in terms of Ozone Depletion Potential (ODP) among other studied H_2 production processes, coal gasification, and PEM electrolysis as shown in Figure 3(c). ODP score for PEM electrolysis Hydrogen production was found very high almost 100 times greater than that of Hydrogen production from biogas generated via co-digestion of poultry droppings and wheat straw and it was 1.22×10^{-5} kg CFC-11-Eq / kg H_2 and for coal gasification process, it was found 10 times greater having the value as 3.35×10^{-6} kg CFC-11-Eq / kg H_2 [6]. The hydrogen production process that we investigated also demonstrated superior performance in the category of Particulate Matter Formation (PMFP). The impact evaluation showed that its environmental impact was about 50% lower than the non-renewable coal gasification process, which had 0.04 kg PM_{10}-Eq/ kg H_2, the worst case as shown in the graph of Figure 3(d). This shows that industrial raw materials cause most of coal gasification's environmental impacts. Electrolysis with the proton exchange membrane having a value of 0.033 kg PM_{10}-Eq/ kg H_2 resulted in this category better than coal gasification while being more energy-intensive because water is the primary raw material for hydrogen production [6]. Terrestrial acidification (TAP) is mostly caused by the combustion of coal, resulting in the significant emission of carbon dioxide (CO_2) into the atmosphere. In addition, coal that contains a high concentration of sulfur emits sulfur dioxide (SO_2), a compound that contributes to the process of acidification. Hence, the coal gasification process of hydrogen production contributes more to this impact category than our studied process and electrolysis process as shown in Figure 3(e).

Differences in assumptions and system boundary conditions for different hydrogen production routes may be considered as one of the limitations of this study. Some of the further works that can be carried out in the future are: Co-digestion using different combinations of biomass to evaluate any variation in the amount of biogas production can be carried out, comparing steam reforming method with dry reforming one to evaluate the impact categories, comparing anaerobic co-digestion data with other emerging renewable hydrogen production routes, sensitivity analysis of the process can be examined addressing various uncertainties, and different construction material and transportation method can be considered for better environmental impact result.

4. Conclusion

The life cycle impact assessment has been conducted in this research study between hydrogen production from dry reforming of biogas produced by co-digestion of poultry droppings and wheat straw and two other approaches, renewable PEM electrolysis and non-renewable coal gasification process using the software openLCA version 1.10.3 and ReCiPe Midpoint (E) as the impact assessment method. It shows that our studied process performs better in the majority of impact categories. It has a far lower influence on climate change, ozone depletion, particle matter formation, and terrestrial acidification due to being a less energy-intensive and waste utilization process. Despite having a greater influence in the category of freshwater eutrophication due to the emission of nutritional minerals in the form of digestate sludge, this method can be considered the most effective among the three methods compared. After considering all the characteristics of hydrogen production from dry reforming of biogas produced by co-digestion, this process can be recommended as a viable and sustainable pathway for hydrogen production.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: Life Cycle Inventory Data for 1 kg Hydrogen production through dry reforming of biogas produced via anaerobic co-digestion of biomass.

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Conflicts of Interest: The authors declare no conflict of interest.

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