

A Mini-Review on Plasma Technology for Hydrogen Productions towards the Transition of Net-Zero Economy from Biomass: The Key Operating Parameters

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Abstract

During the last decades, the interest on the transition to net-zero economy, focusing on hydrogen (H₂) energy, has emerged in an atmospheric-pressure microwave plasma reactor for converting biomass. Unfortunately, the obstacle of microwave plasma is the high energy consumption and proper selection of carrier gases. Thus, a better insight associated with microwave power set up is not only the main key to tackle these issues, but also is one of the primary factors to driving plasma technology forward. This mini-review paper identifies carrier gases, microwave power, flow rate and various issues as the most important points to produce high concentration of H₂ as the possible gas in plasma technology systems. Also, it gives an insight about the conversion route of biomass to obtain the H₂ and supporting the transition of net-zero economy. Economic issues are the main issues to implement the large-scale reactors, especially in energy consumption and carrier gases selection. Therefore, better understanding on operational parameters are required to develop the proper treatment to generate H₂.

Keywords: *H₂ productions, net-zero economy, microwave plasma, plasma technology, transition.*

1. INTRODUCTION

Plasma synthesize for hydrogen (H₂) production has gained an attention over the last decade and become one of promising technologies for addressing the transition to net-zero economy. As a cutting-edge technology, plasma pyrolysis plays an essential role in converting biomass to synthesize H₂ (Lin, 2014) and it able to combat climate change, focusing on reducing CO₂ emissions (Ogwumike et al., 2024). Near the future, H₂ is considered as the renewable energy to replace fossil fuels, especially from the biomass. H₂ from biomass is known as clean, versatile and favorable alternative energy (Ainas et al., 2017).

Plasma consists of different particles, molecules, radicals, atoms, ions and electrons, where the entire density of plasma can be split into density of single species (Leins, 2010). Benefits of using plasma technology because of their high temperature (Samal, 2017), presence of excited species (Samal, 2017), high reaction kinetics (Samal, 2017), high energy density (Samal, 2017), and heat produce because of collisions (Samal, 2017). Biomass from plant-based materials as the source of H₂: algae-based, cellulose-based, and waste-activated sludge biomass have been used widely (Mishra et al., 2023). Cellulose and hemicellulose are primary components of biomass (Elhambakhsh et al., 2023). Cellulose and hemicellulose in biomass have resulted in higher production of H₂ in terms of bioenergy conversion (Parthasarathy and Narayanan, 2014). It is trustworthy that cellulose in biomass is cost-effectiveness and richness (Jara-Cobos et al., 2023). Also, materials from plasma post-treatment has been considered in the advantages for recycling applications, such as bio-char in adsorption (Dermawan et al., 2022; Sanito et al., 2020b) and carbons combined with semiconductor materials for photocatalyst application (Sanito et al., 2023c). Antunes et al. (2025) reported that catalyst-free microwave may produced 99% H₂ of conversion of ammonia (NH₃), where the largest energy yield of H₂ was 447 LH₂ kWh⁻¹. H₂ gas yield may be obtained at 37.58% from micro algae after treatment with microwave plasma reactor (Chang et al., 2020). Unfortunately, the implementations associated with the proper set up of parameters in plasma technology are still unknown. Also, it many researchers claim that cost issues in set up of parameters are still main constrains, since it has direct impact towards the implementation in the large-scale applications (Gomez et al., 2009; Heberlein and Murphy, 2008; Sanito et al., 2023a; Sanito et al., 2022b; Sanito et al., 2020a; Sanito et al., 2020b; Sanito et al., 2021; Sikarwar et al., 2020). Thereby, plasma

technology, namely atmospheric-pressure microwave plasma reactor (Lin et al., 2014; Lin, 2014; Sanito et al., 2022), has been widely used for pyrolysis of biomass to obtain H₂ as an alternative energy for the transition of net-zero economy.

Hence, the goals of this mini-review paper are to address the major problems on technical issues in the plasma reactor, as well as give an overview of important parameters of plasma reactor, synthesize mechanism of H₂, and cost-issues of treatment for the transition of net-zero economy. This mini-review summarizes the experimental data and review paper on plasma technology as the main information from publication indexed by scopus and science direct.

2. PARAMETERS IN MICROWAVE PLASMA REACTOR

This section is kicked-off by analysis of the important parameters in pyrolysis of biomass to synthesize H₂. Information of parameters is given as follow: pyrolysis duration, type of carrier gas, gas flow rate and power set-up (Lin et al., 2014; Lin, 2014; Sasujit et al., 2022). Reactors are operated in atmospheric-pressure with value at approximately 760 Torr. In this review **Figure 1** gives an illustration about the design reactor of atmospheric-pressure microwave plasma.

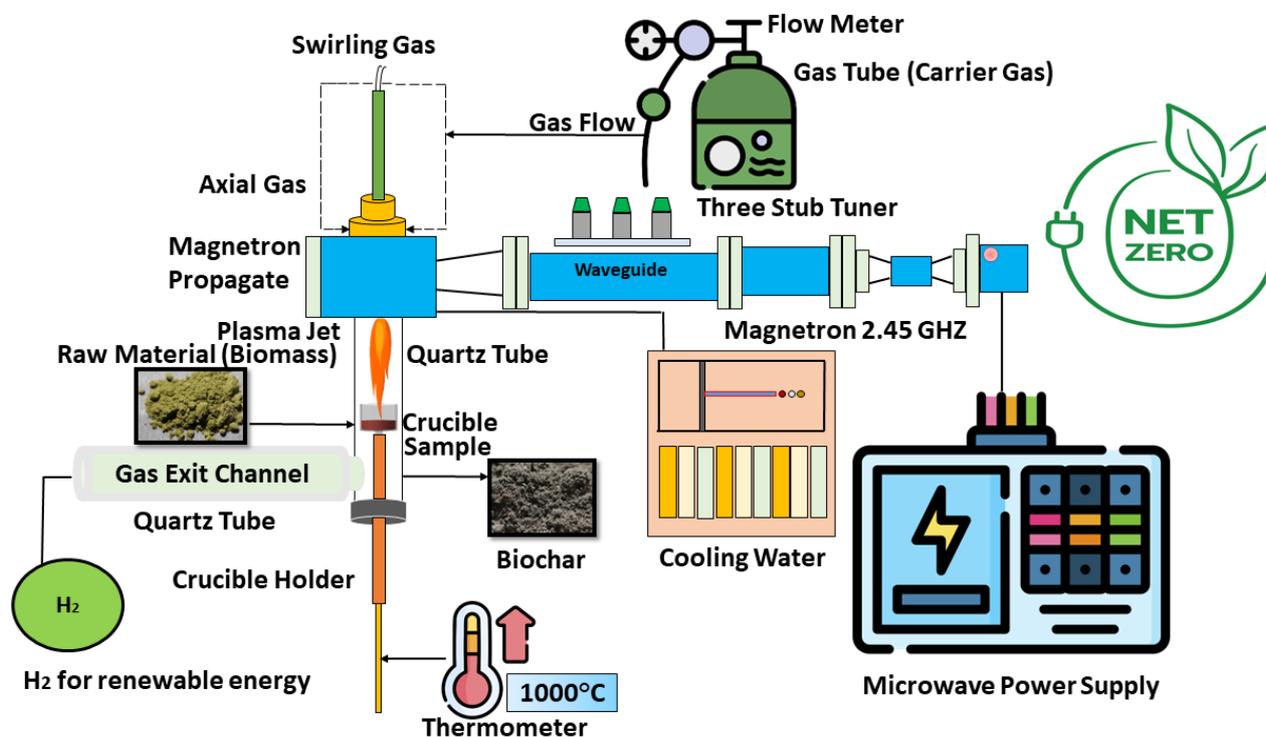


Figure 1. Illustration of microwave plasma to generate H₂ as resource of renewable energy

2.1. PLASMA PYROLYSIS DURATION

In operation of atmospheric-pressure microwave plasma, control of time plays a significant impact on pyrolysis of biomass. Longer duration of pyrolysis increases higher temperature in the reactor. As a result, higher reaction occurs, and it creates the reaction faster to degrade biomass. The composition of biomass that mostly contain of cellulose that able to be degraded via the proper set up of duration in the reactors (Cubas et al., 2015; Sanito et al., 2022; Sanito et al., 2020a).

2.2. CARRIER GAS

A carrier gas is used to create the plasma discharge in the microwave reactor plasma. Gases of plasma contains of neutrals of ions and electrons. In addition, charged particles leads to the conditions that plasmas behave contact with the electromagnetic fields. (Leins, 2010) Electron densities range

about 10^{30} m^{-3} . However, it depends on type of gases that is used during the experiments. For example: N_2 has lower molecular weight compared to Ar with value 28,020 (Nur, 2011) and wavelength of N_2 798 Å.

A report from Sanito et al. stated that different set up of carrier gas during experiment has an impact towards the result of samples (Sanito et al., 2022b). It is caused by the particle collision of electrons during the pyrolysis (Leins et al., 2015) and higher arc of plasma discharge (Heberlein and Murphy, 2008). Thus, it can be understood that different carrier gases have different impact toward the experimental results.

2.3. POWER SET-UP

It is necessary to understand that higher microwave power of atmospheric pressure microwave plasma reactors creates the higher volume of plasma discharges (Leins et al., 2012). Proper set up of microwave power is started from 700 to 1400 W, with the maximum set up is not more than 2000 W (Sanito et al., 2022). Set up higher than 2000 W in the system potentially causes the problem for the tungsten of plasma machine, cracking of the tubes due to high temperature over 1000°C . Thus, a proper set up is needed to be considered during the plasma treatment. In the case of reverse vortex flow gliding arc plasma discharge reactor (RVF-GAD). Power supply instruments are used as a high-voltage neon AC transformer, where the transfer of the voltage ranging from 0 to 220 V-rms to 0 – 15 kV (Sasujit et al., 2022).

2.4. FLOW RATE CONTROL

The function of flow rate in plasma is to control the flow of the carrier gas from the tube, which be able to create the plasma discharge from the reactors systems. From this point of view, the flowing gas flow rate will be able to create a high temperature plasma discharge, where it depends on control of the flow rate. Lower flow rate set-up with higher control of microwave power has an impact towards the better set up of discharge. For instance: the set up of flow rate at 30 sl/min indicates a longer volume of discharges compared to 70 sl/min in axial and radial directions (Leins et al., 2012).

3. H_2 SYNTHESIZE VIA A MICROWAVE PLASMA REACTOR

Synthesize of H_2 of plasma reactor has been identified by researchers in order to obtain the optimum results of biomass/ synthesize. It depends on the reactor designs because the set-up of parameters is usually different. Following setup is described as follow from researchers in an atmospheric-pressure microwave plasma reactor system:

- Applied microwave power were controlled at 800 W (Chang et al., 2020; Lin et al., 2014; Lin, 2014), 900 W (Chang et al., 2020; Lin et al., 2014; Lin, 2014), 1000 W (Chang et al., 2020; Lin et al., 2014; Lin, 2014; Sanito et al., 2022), 1100 W (Chang et al., 2020) and 1200 W (Sanito et al., 2022).
- Temperatures of plasma zone are set up at 1063, 1093 and 1121 K (Lin, 2014), $700\text{-}800^\circ\text{C}$ (Chang et al., 2020; Sanito et al., 2022).
- Nitrogen (N_2) is used as the carrier gases to create plasma discharge (Chang et al., 2020; Leins et al., 2015; Lin, 2014).
- Flow rate controlled at 9 L min^{-1} and 12 L min^{-1} (total of axial flow rate and swirl flow rate) (Chang et al., 2020; Li et al., 2014; Lin, 2014; Sanito et al., 2022).
- Pyrolysis durations are 5 min (Sanito et al., 2022) and 7 min (Sanito et al., 2022).

The presence of contents related to C, H, and O of biomass is associated with the presence of carbohydrate isomers to cellulose monomer ($\text{C}_6\text{H}_{10}\text{O}_5$). Cellulose, hemicellulose and lignin play a pivotal role in distribution of H_2 (Sikarwar et al., 2020). It confirms that composition of this biomass consists of cellulose. During the pyrolysis of biomass, it transforms the cellulose into H_2 . Gaseous products are generated via devolatilization, gas phase in secondary reactions, and char gasification. The result of devolatilization process of biomass is related to decomposition of the cellulose-containing solid, intermediate gases, and solid residue (char) (Calonaci et al., 2010). Dehydration reactions generate chars

from active cellulose. Furthermore, it produces volatile species and char (Lin, 2014). According to Boules (Boules et al., 2024), decomposition cellulose obtain anhydrosugar oligomers, which is transformed into furans, levoglucosan, and other oxygenated species. Volatiles products are glycolaldehyde ($C_2H_4O_2$), glyoxal ($C_2H_2O_2$), acetaldehyde (CH_3CHO), acetone (C_3H_6O), hydromtehylfurfural ($C_6H_6O_3$), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), water (H_2O) and levoglucosan ($C_6H_{10}O_5$). The secondary gas-phase reactions generate H_2 associated with the H_2 abstraction reactions by the H_2 atoms towards the volatile products (Lin, 2014). Illustration is given in **Figure 2**.

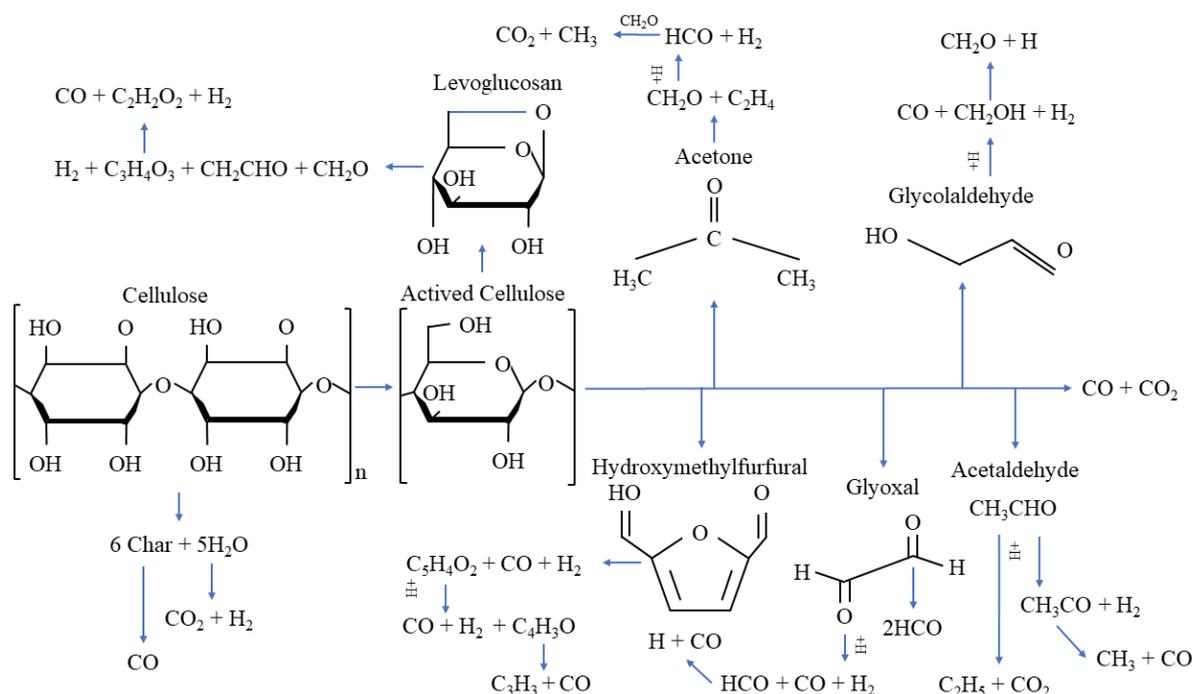


Figure 2. Mechanism of reaction pathway of biomass in the plasma pyrolysis. Illustrations are modified from Sanito et al. (Sanito et al., 2022), Lin et al., (2014a) and Lin et al., (2014b).

One of key factor to improves the H_2 formation is with increase the temperature with raising the power level of microwave energy that related to the high-temperature pyrolysis refers to dehydrogenation reactions of aromatic hydrocarbons and change of reaction pathway. Also, the total volume of flow rate that enter to the reactor is believed has an impact towards H_2 . It is also be believed that modification of heat insulation in the plasma core will have an impact towards thermal-to- H_2 efficiency and increase of power has an impact towards the conversion rate by a factor up to 2.5 (Jasiński, 2008; Lin et al., 2014; Lin, 2014). High reaction power decreases the CO volume fractions and at the same time increase the concentration of H_2 (Hu, 2004). From this standpoint of view, proper control of microwave power is a must to obtain the optimum results.

The ion bombardment of the biomass with high energetic electrons, ions, radicals, has an impact towards dehydrogenation via the separation of $C-H$ bond in the biomass (Bruggeman et al., 2017). Plasma species has a significant impact towards the heating of biomass on its surface (Tabu et al., 2022). From this point of view, lignocellulose from biomass can be degraded perfectly due to degradation process during plasma pyrolysis. Until recently, report on the impact of carrier gases, flow rate controls and pyrolysis time has not explained further in details. It means that the impact of these parameters are not discussed in further details due to limitation of instruments for the analysis. It is only less information on that in journal publications. Thus, further information associated with effect of carrier gases should be studied, especially focusing on kinetic energy and collision of particles in plasma ionization. Carrier

gases in plasma pyrolysis play a pivotal role to create an ionization, responsible for excitation that create collision of atoms. As a result, it generates H₂ as the product from the reactions. Results of H₂ production from different biomass are explained in **Table 1**.

Table 1. Treatment of Biomass via Plasma Technology to generate H₂

Biomass	Parameters			H ₂ Production	References
	Flow Rate	Power Setting	Pyrolysis Duration		
<i>Eichhornia crassipes</i>	9 SLM	1000 W	7 Min	56.28%	Sanito et al., (2022)
<i>Pistia stratoites</i>	9 SLM	1000 W	7 Min	57.30%	Sanito et al., (2022)
<i>Ficus</i> sp.	12 SLM	800 W	N/A	35.05%	Lin et al., (2014a)
<i>Ficus</i> sp.	12 SLM	900 W	N/A	51.85%	Lin et al., (2014a)
<i>Ficus</i> sp.	12 SLM	1000 W	N/A	67.33%	Lin et al., (2014a)
Spirulina algae	12 SLM	800 W	N/A	90.56%	Lin et al., (2014b)
Spirulina algae	12 SLM	900 W	N/A	89.57%	Lin et al., (2014b)
Spirulina algae	12 SLM	1000 W	Not Mentioned	88.97%	Lin et al., (2014b)

From the table 1, it can be seen that the higher control of microwave power with value 1000 W has a direct impact towards the H₂ production in the systems, with the value more than 50%. On the other hand, lower control of microwave power indicates the percentage of H₂ is lower than 50%. Interestingly, despite there is a lower control of microwave power at 800 W, higher control of gas flow rate has an impact towards the result of H₂ that reached 90.56%, with specific control of N₂ flow rate at 12 SLM. From this point of view, it is clear that flow rate of gases has an impact towards the conversion efficiency of H₂. The production of H₂ with lower control of gas flow rate may be due to the low reactive species production in the plasma pyrolysis reaction, even the microwave power input is stable. Thus, higher control of flow rate has a direct impact towards the production of H₂ percentages.

Energy production costs for argon-plasma-treated is higher compared to N₂ (Boules et al., 2024). Energy production costs for cellulose is 600 mol/kWh (Tabu et al., 2024). From this reason, a proper analysis must be conducted associated with cost issues related to implementation of microwave plasma for dealing with biomass.

4. TRANSITION TO NET-ZERO EMISSION FROM BIOMASS

Transition to Net-Zero Economy by 2050, decreasing greenhouse gas (GHG) emissions and finding renewable energy sources become main issues. In addition, circular bioeconomy to fulfill the concept of sustainable development goals (SDGs) aims to provide the clean energy. H_2 derived from biomass is one of the primary key for the circular economy due to its advantages toward sustainable development. The main idea of the net zero economy includes the stability between GHG emissions and decrease of GHG emissions.

A concept of bio-circular economy, the sustainability framework, is required to optimize the efficiency resource as well as promoting the utilization of renewable resources. It requires the concept of close loop system where the systems use the valuable input that able to reduce the impact of waste to environment (Ubando et al., 2020). In the treatment, biomass from various resources, such as agricultural waste, macro algae and floating plants, can be used in plasma pyrolysis, result in H_2 production. **Figure 3** indicates an illustration of this idea based on the concept to adapt a strategy associated with H_2 productions. Lin (2014) confirmed the possibility to use banyan leaves to generate H_2 via an atmospheric-pressure microwave plasma reactor to fulfill the concept of circular bio-economy. Sanito, et al. (2022) reported a potential use of *E. crassipes* and *Pistia stratoites* to generate H_2 , confirming the application of circular bioeconomy due to the reuse of crops from the post-treatment of phytoremediation. Thus, the strategy related to the circular bioeconomy can be able to reduce the solid waste, maximize the potential of biomass and support the implementation of H_2 production.

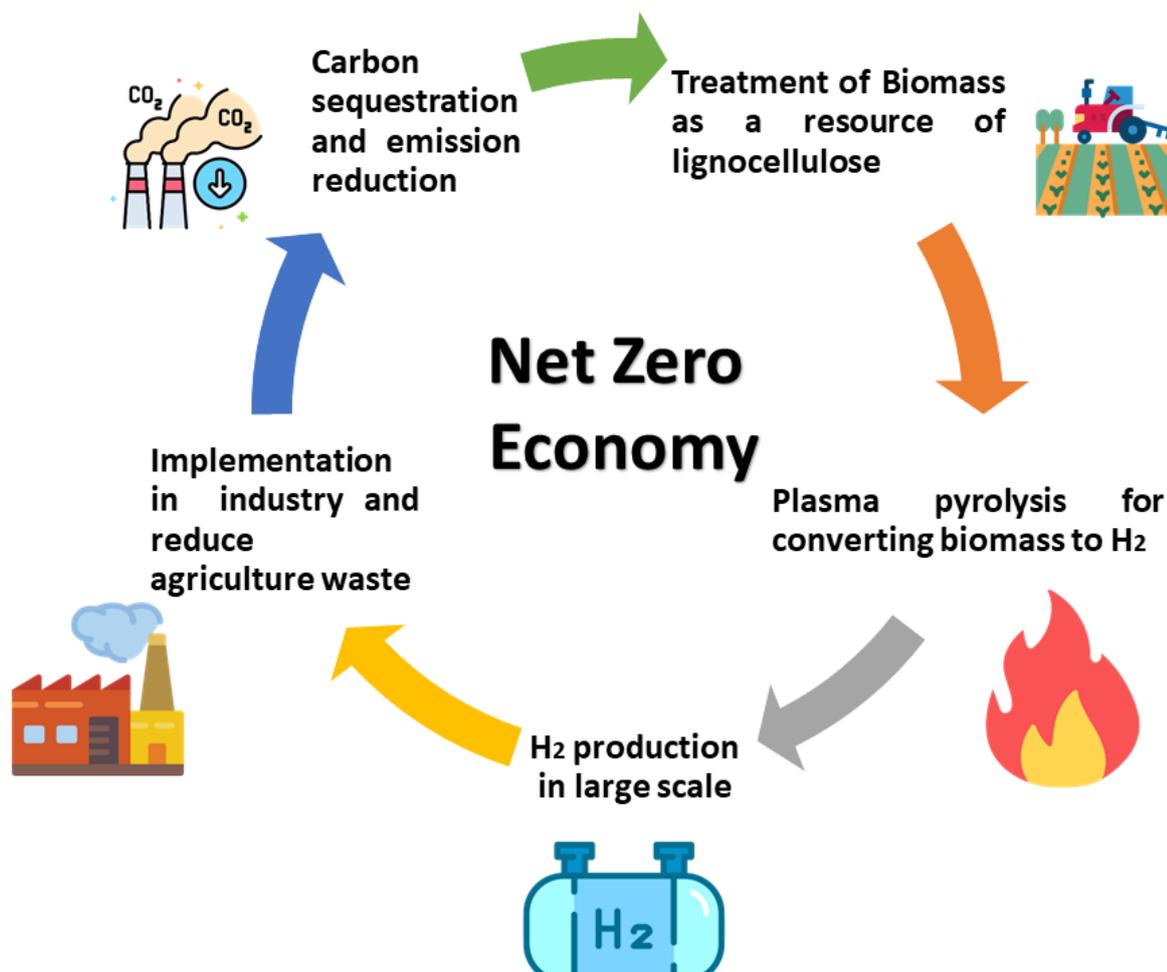


Figure 3. Illustration of circular economy to obtain net zero 2050 with the implementation of plasma pyrolysis of biomass.

During the concept for dealing with biomass associated with net-zero bioeconomy, it is associated to reduce the amount of biomass that have an impact towards reduce of environmental pollution in atmosphere. The concept is developed to ensure the sustainable of biomass, decrease the environmental issues and contributing to circular bioeconomy concept. In addition, the use biomass residue ensures waste minimization. For example: the use of *E. crassipes* from the post-treatment in the remediation fields can be considered as the raw material for H₂ production instead of animal feed. From this point of view, *E. crassipes* can be used in plasma pyrolysis in order to obtain H₂. Lin et al. (2014) stated that H₂ formation can be obtained with the proper control of microwave power during the pyrolysis of *Spirulina* algae. From this point of view, potential H₂ can be obtained during the study. Thus, the different sources of biomass can be used as the raw material to generate H₂ and at the same time, the concentration of CO₂ can be reduced. Higher temperature causes dehydrogenation reactions that responsible to degrade aromatic hydrocarbons (Sikarwar et al., 2020). It is clear that proper control of plasma parameter has a direct impact towards the output of the research and able to fulfill the concept of net-zero economy emissions.

5. CHALLENGE AND PROSPECT OF PLASMA PYROLYSIS–H₂ PRODUCTION

The specific information of atmospheric-pressure microwave plasma reactor for generating H₂ in terms of economic evaluation is still limited due to the lack of literature information. This section provides an information related to challenge and prospect of plasma pyrolysis in general. Implementation of H₂ production via biomass faces challenges that related to its widespread applications. High energy consumption (Sanito, 2021; Sanito et al., 2020b), operational costs (Cvetinović et al., 2025; Wang et al., 2025), carbon handling, scale-up limitations, process optimization and competition with other H₂ technologies (Anand et al., 2025). Addressing these obstacles can also have opportunities to mitigate CO₂ issues. Also, it has a chance to promote the sustainability. The main challenges to implement plasma technology is high cost (Samal, 2017) and more suitable for dealing with hazardous waste due to its robust installation and fast reaction performance (Heberlein and Murphy, 2008; Sanito, 2022; Sanito et al., 2022; Sanito et al., 2024; Sanito et al., 2021). It requires lots of electricity consumptions (Gomez et al., 2009; Sanito, 2022). However, since the pyrolysis of biomass has been conducted by some scholars, the potential to generate H₂ can be considered but required further study (Chang et al., 2020; Dermawan et al., 2022; Sanito et al., 2022). Also, the production costs are predicted ranging from \$ 1.21 – \$ 2.42 per kg of samples should be analyzed to understand their feasibility in the real world (Anand et al., 2025). However, there is an opportunity to reduce the electricity cost, especially to reduce the H₂ production cost (Cvetinović et al., 2025). However, it is still doubt whether it can be applied in the real case. There are reports associated with the shutdown of reactors because of financial constrain, especially in Japan (Sikarwar et al., 2020). In laboratory scale, technical issues are associated with high consumption of electricity with longer pyrolysis time and price of carrier gases (Sanito, 2020; Sanito et al., 2023a; Sanito et al., 2020b). Another obstacle for the application of microwave plasma technology for synthesizing H₂ is potential to generate formation of volatile organic compounds (VOCs), both from carbon sources (biomass and other materials) (Sanito et al., 2022a; Sanito et al., 2023b; Sanito et al., 2022; Sanito et al., 2022b; Sanito et al., 2020a; Sanito et al., 2022) and tar (Sasujit et al., 2022). Thereby, production of H₂ may be considered as the side product.

Furthermore, a combination of plasma with carbon capture technology is believed may improve the high purity of H₂. A design of carbon capture technology may be installed with the plasma technology reactors. It potentially can reduce the CO₂ concentration from the process of plasma pyrolysis. According to Anand et al. (2025) pyrolysis can be considered as carbon-neutral or carbon negative due to an equivalent perspective towards the CO₂ capture by plants during their growth process. Also, biochar, the result of post-pyrolysis, can be used to improve the quality of soil as fertilizer. Thus, it can be understood that implementation of plasma technology in industrial application for H₂ production is a promising stage for controlling CO₂ emissions as well as fulfill the concept of sustainability and circular economy.

6. CONCLUSION

At present, the use of plasma technology, namely atmospheric-pressure microwave plasma is still the biggest challenge and major barriers for the implementation in the real world. During the treatment of biomass, different set-up of microwave power and gas flow rate of carrier gases causes a complicated production of H₂, playing an important role as key operating parameters. High costs are main issues to implement the large-scale reactors not only for the electricity consumption but also carrier gases and production because they have a direct impact towards the performance of H₂ production. Despite microwave plasma has a huge potential, many factors that caused the limitation in the implementation of biomass treatment remain in evidence. Therefore, better understanding of all plasma parameters of microwave plasma to develop proper treatment and implementation is suggested for the transition of net-zero bioeconomy to control GHG emissions.

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