



# Analysis of Green Hydrogen Potential from Biomass Waste in Indonesia: Resource Availability, Energy Potential, and Techno-Economic Feasibility

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## ABSTRACT

Indonesia possesses abundant biomass waste resources generated from agricultural, plantation, forestry, and municipal activities, creating significant opportunities for green hydrogen production as part of the transition toward sustainable and low-carbon energy systems. This study aims to analyze the potential of biomass waste as a feedstock for green hydrogen production in Indonesia and evaluate its contribution to national energy security and decarbonization objectives. The research employs a quantitative assessment approach supported by a systematic literature review, utilizing secondary data from government reports, statistical databases, and scientific publications. The methodology includes biomass resource assessment, hydrogen yield estimation, energy potential calculation, environmental impact evaluation, and techno-economic feasibility analysis. The results indicate that Indonesia possesses substantial biomass waste resources, with palm oil residues, rice husks, sugarcane bagasse, coconut shells, forestry residues, and municipal organic waste representing the most significant feedstocks. Among these resources, palm oil biomass demonstrates the highest hydrogen production potential due to its large availability and favorable conversion characteristics. Environmental analysis reveals that biomass-derived hydrogen can reduce landfill dependency, minimize open biomass burning, decrease greenhouse gas emissions, and support circular economy practices through waste valorization. Nevertheless, challenges related to feedstock variability, conversion efficiency, infrastructure limitations, investment costs, and regulatory frameworks remain barriers to large-scale deployment. Overall, the findings demonstrate that biomass waste has considerable potential to support Indonesia's green hydrogen development, strengthen energy security, promote sustainable waste management, and contribute substantially to national decarbonization and renewable energy transition goals.

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## 1. INTRODUCTION

The global energy sector is undergoing a significant transformation driven by the urgent need to mitigate climate change and achieve carbon neutrality. The increasing concentration of greenhouse gases (GHGs) in the atmosphere, largely resulting from the combustion of fossil fuels, has accelerated global warming and intensified environmental degradation (Kumar, 2018). In response, many countries have committed to reducing carbon emissions and transitioning toward sustainable energy systems. The pursuit of net-zero emissions has encouraged the development and adoption of renewable energy technologies that can provide clean, reliable, and environmentally friendly alternatives to conventional fossil-based energy sources.

Despite their dominant role in meeting global energy demand, fossil fuels such as coal, oil, and natural gas present numerous challenges. Their finite availability raises concerns regarding long-term energy security, while their extraction, processing, and combustion contribute significantly to greenhouse gas emissions. Moreover, fluctuations in fossil fuel prices and geopolitical uncertainties can adversely affect economic stability and energy accessibility. Consequently, there is a growing interest in alternative energy carriers capable of supporting decarbonization efforts while maintaining energy reliability and sustainability.

Hydrogen has emerged as one of the most promising clean energy carriers for the future (Hoffmann, 2012). Unlike fossil fuels, hydrogen utilization produces water as the primary by-product when used in fuel cells or combustion systems, making it a potentially carbon-free energy source. Hydrogen can be applied across various sectors, including transportation, power generation, industrial manufacturing, and energy storage. However, the environmental benefits of hydrogen depend heavily on its production pathway. Hydrogen is commonly categorized into grey, blue, and green hydrogen. Grey hydrogen is produced primarily from fossil fuels without carbon capture, resulting in significant carbon emissions. Blue hydrogen utilizes similar fossil-based processes but incorporates carbon capture and storage technologies to reduce emissions. Green hydrogen, on the other hand, is produced from renewable resources and low-carbon processes, making it the most environmentally sustainable option among the three.

Indonesia has demonstrated a strong commitment to reducing greenhouse gas emissions and supporting the global energy transition. Through its Nationally Determined Contribution (NDC) and long-term low-carbon development strategies, the country aims to significantly reduce emissions while increasing the share of renewable energy in its national energy mix (Fragkos et al., 2017). Achieving these goals requires the exploration of diverse renewable energy resources that can support both energy security and environmental sustainability. Among the available options, biomass waste represents a particularly attractive resource due to its abundance and widespread availability across the country.

As one of the world's largest agricultural producers, Indonesia generates substantial quantities of biomass waste annually. Major sources include palm oil empty fruit bunches (EFB), palm kernel shells, rice husks, sugarcane bagasse, coconut shells, corn residues, forestry residues, and municipal organic waste. Much of this biomass remains underutilized or is disposed of through open burning and landfilling, practices that contribute to environmental pollution and greenhouse gas emissions. Converting biomass waste into green hydrogen offers a promising solution for simultaneously addressing waste management challenges and supporting renewable energy development.

Biomass waste possesses several characteristics that make it an attractive feedstock for hydrogen production (Ntaikou et al., 2010). First, it is a renewable resource generated continuously through agricultural, forestry, and municipal activities. Second, its abundant availability provides a stable and sustainable supply of feedstock for large-scale hydrogen production. Third, biomass waste is generally low-cost compared to dedicated energy crops or fossil fuel resources, thereby enhancing economic feasibility. Furthermore, utilizing biomass waste can reduce environmental problems associated with waste disposal, including methane emissions from landfills and air pollution from open burning. These advantages position biomass waste as a strategic resource for supporting the development of a green hydrogen economy in Indonesia.

Research on green hydrogen production from biomass waste has gained significant attention over the past decade due to increasing concerns regarding climate change, energy security, and the transition toward low-carbon energy systems. One of the earlier comprehensive studies in this field

was conducted by Sarkar and Kumar (2016), who examined the potential of biomass gasification technologies for sustainable hydrogen production. Their study highlighted gasification as one of the most promising thermochemical pathways because of its high conversion efficiency and ability to process a wide range of biomass feedstocks. The authors emphasized that agricultural residues and forestry wastes could serve as sustainable feedstocks for large-scale hydrogen generation.

Subsequently, Balat (2018) analyzed various renewable hydrogen production technologies and compared their environmental performance. The study concluded that biomass-based hydrogen production offers significant advantages over fossil fuel-derived hydrogen due to lower lifecycle greenhouse gas emissions and the utilization of renewable feedstocks. Furthermore, the research identified biomass gasification as a mature technology with considerable potential for commercial deployment.

A major contribution to the understanding of biomass-derived hydrogen was provided by Raza et al. (2020), who investigated biomass conversion routes and their integration within circular economy frameworks. Their findings demonstrated that biomass waste can simultaneously address waste management challenges and renewable energy production objectives. The study emphasized the importance of utilizing agricultural residues that would otherwise be disposed of through open burning or landfilling.

Research attention expanded toward lignocellulosic biomass as a hydrogen source in recent years. Marcello et al. (2023) conducted a comprehensive review of hydrogen production from lignocellulosic biomass and evaluated thermochemical technologies such as gasification, pyrolysis, and liquefaction. Their findings revealed that gasification remains the most technologically advanced approach, while pyrolysis offers additional opportunities for producing valuable by-products. The study concluded that abundant agricultural and agro-industrial residues represent significant feedstock resources for sustainable hydrogen production.

In 2024, biomass-derived hydrogen became an increasingly important research area due to growing global interest in green hydrogen economies. Damiri et al. (2024) reviewed alternative green hydrogen production pathways focusing specifically on biomass utilization. Their study compared thermochemical, biochemical, and electrochemical conversion methods and found that thermochemical routes generally provide higher hydrogen yields and greater scalability for industrial applications. The authors also emphasized the importance of integrating biomass hydrogen systems with existing renewable energy infrastructures.

Similarly, Taqvi et al. (2024) provided a state-of-the-art review of biomass gasification technologies. Their research examined feedstock characteristics, gasifier designs, syngas production mechanisms, and hydrogen recovery techniques. The study demonstrated that advancements in gasification technology have significantly improved hydrogen production efficiency while reducing operational costs, making biomass gasification increasingly attractive for commercial deployment.

A comprehensive techno-economic and environmental assessment was conducted by Ghasemi, Rad, and Akrami (2024). Their review evaluated multiple biomass-to-hydrogen pathways, including thermochemical, biological, and electrochemical conversion processes. The researchers found that thermochemical technologies, particularly gasification and steam reforming, exhibit the highest technological readiness levels and scalability potential. However, they also noted that economic competitiveness remains dependent on feedstock availability, process optimization, and policy support mechanisms.

Within the Indonesian context, Budhijanto and Pancasakti (2024) investigated hydrogen production from agricultural waste through a comparative techno-economic analysis. Their study evaluated supercritical water gasification (SCWG), fermentation, and gasification technologies under Indonesian conditions. The results suggested that agricultural waste possesses considerable potential as a feedstock for hydrogen production and that fermentation-based processes could offer favorable economic performance under certain operational conditions. The study provided one of the first quantitative assessments specifically focused on Indonesia's agricultural biomass resources.

Despite its considerable potential, the utilization of biomass waste for hydrogen production in Indonesia remains limited (Susilaningsih et al., 2014). Existing studies have primarily focused on biomass for electricity generation, biofuels, and direct combustion applications, while comprehensive

assessments of hydrogen production potential remain relatively scarce. In addition, the actual quantity of biomass waste available for sustainable hydrogen production has not been fully quantified at the national level. Questions also remain regarding the economic feasibility of biomass-based hydrogen production technologies and their environmental benefits compared with conventional fossil fuel-based hydrogen pathways.

Based on these considerations, several research questions arise: How much biomass waste is available in Indonesia for hydrogen production? How much green hydrogen can potentially be generated from these biomass resources? Which biomass feedstocks offer the highest hydrogen production yields? What environmental advantages can be achieved through biomass-derived hydrogen compared with fossil fuel-based alternatives? Finally, what technical, economic, and policy challenges must be addressed to facilitate the commercialization of biomass-based green hydrogen in Indonesia?

Therefore, this study aims to identify biomass waste resources suitable for hydrogen production in Indonesia, estimate their potential contribution to green hydrogen generation, evaluate associated environmental impacts, assess economic feasibility, and formulate policy recommendations to support future development. By providing a comprehensive analysis of biomass-derived hydrogen opportunities, this research contributes to the growing body of knowledge on renewable hydrogen production and sustainable energy systems.

The significance of this study extends across multiple dimensions. From an academic perspective, it expands existing knowledge regarding the utilization of biomass waste as a renewable feedstock for green hydrogen production. From an industrial perspective, the findings can support investment decisions and technological development within Indonesia's emerging hydrogen sector. From a governmental perspective, the study provides valuable insights for policymakers in designing strategies and regulations that promote renewable energy adoption, waste valorization, and national decarbonization efforts. Ultimately, the development of green hydrogen from biomass waste has the potential to contribute significantly to Indonesia's energy transition, environmental sustainability, and long-term energy security.

## 2. RESEARCH METHOD

This study employs a quantitative assessment approach supported by a systematic review of relevant literature to evaluate the potential of biomass waste as a feedstock for green hydrogen production in Indonesia. The research integrates biomass resource assessment, hydrogen production estimation, environmental impact evaluation, and techno-economic analysis to provide a comprehensive understanding of the feasibility of developing a biomass-based hydrogen economy. By combining secondary data analysis with established theoretical models, the study aims to estimate the national potential for green hydrogen production and assess its contribution to Indonesia's renewable energy transition.

The research design consists of two complementary approaches. First, a Systematic Literature Review (SLR) is conducted to identify and analyze previous studies related to biomass resources, hydrogen production technologies, environmental sustainability, and economic feasibility. The literature review provides a theoretical foundation for understanding the current state of biomass-based hydrogen production and identifying suitable conversion technologies for Indonesian conditions. Second, a quantitative assessment is performed to estimate the amount of hydrogen that can theoretically be produced from available biomass waste resources in Indonesia. This approach enables the evaluation of hydrogen production potential at a national scale and facilitates comparisons among different biomass feedstocks.

The study relies entirely on secondary data collected from various reputable sources (Vartanian, 2010). Biomass production data are obtained from reports published by the Ministry of Energy and Mineral Resources (MEMR), Statistics Indonesia (BPS), the Food and Agriculture Organization (FAO), government publications, and peer-reviewed scientific journals. Additional information regarding hydrogen yields, conversion efficiencies, energy contents, and emission factors is collected from international research articles and technical reports. The collected data include annual agricultural production, biomass waste generation rates, hydrogen conversion yields, calorific values, and greenhouse gas emission factors. These datasets serve as the basis for

estimating biomass availability, hydrogen production potential, energy output, and environmental impacts.

To determine the quantity of biomass waste available for hydrogen production, a biomass resource assessment is conducted (Esteban & Carrasco, 2011). The annual biomass waste generation is estimated using the relationship between agricultural production and waste generation rates. Biomass waste availability is calculated using the following equation:

$$BW = AP \times WR$$

where  $BW$  represents the quantity of biomass waste generated annually (tons/year),  $AP$  denotes agricultural production (tons/year), and  $WR$  refers to the waste generation ratio associated with each biomass source (Buam & Hussain, 2021). This method is widely used in biomass resource assessments because it allows the estimation of waste quantities based on existing agricultural production statistics. The analysis focuses on major biomass waste streams in Indonesia, including palm oil empty fruit bunches, palm kernel shells, rice husks, sugarcane bagasse, coconut shells, corn residues, forestry residues, and municipal organic waste.

Following the estimation of biomass availability, the theoretical hydrogen production potential is calculated using biomass-specific hydrogen yields reported in the literature. The hydrogen production potential is estimated using the following equation:

$$HP = BW \times HY$$

where  $HP$  represents hydrogen production potential ( $\text{kg H}_2/\text{year}$ ),  $BW$  denotes available biomass waste (tons/year), and  $HY$  represents hydrogen yield per unit biomass ( $\text{kg H}_2/\text{ton biomass}$ ). The resulting estimates provide an indication of the maximum quantity of hydrogen that could be produced if available biomass resources were fully utilized for hydrogen generation. The hydrogen production potential is subsequently converted into energy units such as kilowatt-hours (kWh), gigawatt-hours (GWh), or petajoules (PJ) to facilitate comparison with national energy demand.

Several biomass-to-hydrogen conversion technologies are evaluated in this study (Kalinci et al., 2009). Gasification is examined as one of the most mature and widely adopted thermochemical technologies due to its high efficiency and ability to process various biomass feedstocks. During gasification, biomass is converted into synthesis gas (syngas), which can subsequently be processed to produce hydrogen. Pyrolysis is also analyzed because it produces both bio-oil and syngas, creating opportunities for multiple value-added products. Steam reforming of biomass-derived intermediates is evaluated due to its relatively high hydrogen yield and suitability for large-scale production. In addition, biological conversion technologies, including dark fermentation and photo-fermentation, are assessed because they offer environmentally friendly alternatives for hydrogen production under milder operating conditions. The comparative evaluation of these technologies considers conversion efficiency, technological maturity, feedstock compatibility, environmental performance, and economic feasibility.

Environmental assessment is conducted to evaluate the potential contribution of biomass-derived hydrogen to greenhouse gas emission reduction (Navarro et al., 2009). The analysis compares carbon emissions associated with conventional fossil fuel-based hydrogen production and biomass-based green hydrogen pathways. Carbon emission reduction is estimated using the following relationship:

$$CO_2 \text{ Reduction} = \text{Emission}_{\text{fossil}} - \text{Emission}_{\text{green}}$$

where  $\text{Emission}_{\text{fossil}}$  represents emissions associated with conventional hydrogen production technologies and  $\text{Emission}_{\text{green}}$  represents emissions resulting from biomass-based hydrogen production (Megia et al., 2021). The environmental evaluation incorporates Life Cycle Assessment (LCA) principles to examine emissions across the entire production chain, including feedstock collection, transportation, conversion processes, and hydrogen utilization. Carbon footprint analysis is also performed to quantify the overall environmental benefits of biomass-based hydrogen systems.

In addition to technical and environmental assessments, an economic analysis is conducted to determine the financial feasibility of green hydrogen production from biomass waste. The analysis

considers both capital expenditure (CAPEX) and operating expenditure (OPEX) (Ioannou et al., 2018). Capital costs include investments in gasification units, reactors, hydrogen purification systems, storage facilities, and supporting infrastructure. Operating costs include biomass feedstock procurement, transportation, labor, maintenance, utilities, and system operation expenses. To evaluate economic performance, several commonly used financial indicators are employed, including Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PP), and Levelized Cost of Hydrogen (LCOH). These indicators provide insights into project profitability, investment attractiveness, and long-term economic sustainability.

Finally, the results obtained from resource assessment, hydrogen potential estimation, environmental analysis, and economic evaluation are integrated to provide a comprehensive assessment of biomass-based green hydrogen opportunities in Indonesia. The findings are used to identify the most promising biomass resources, evaluate the feasibility of different conversion technologies, and formulate recommendations for policymakers, researchers, and industry stakeholders. Through this integrated methodological framework, the study seeks to provide evidence-based insights into the role of biomass waste in supporting Indonesia's transition toward a sustainable hydrogen economy.

### 3. RESULT AND DISCUSSIONS

#### 3.1 Biomass Waste Availability in Indonesia

Indonesia possesses one of the largest biomass resource bases in the world due to its extensive agricultural, plantation, forestry, and agro-industrial activities. As an agrarian country with vast land resources and favorable climatic conditions, Indonesia generates substantial quantities of biomass waste annually. These biomass residues originate from major sectors such as palm oil plantations, rice cultivation, sugar industries, coconut processing, forestry operations, and municipal waste management systems. The abundance of these resources presents significant opportunities for renewable energy production, including the generation of green hydrogen.

Among the various biomass sources, palm oil waste represents the largest biomass resource in Indonesia (Hambali & Rivai, 2017). The country is the world's largest producer of palm oil, generating significant amounts of residues such as empty fruit bunches (EFB), palm kernel shells, mesocarp fiber, and oil palm trunks. These residues are often underutilized despite possessing considerable energy potential. Rice husks constitute another important biomass resource due to Indonesia's position as one of the leading rice-producing countries globally. Similarly, sugarcane bagasse generated from sugar mills and coconut shells produced by coconut-processing industries contribute substantially to the national biomass inventory. Table 1 presents the major biomass waste sources and their estimated annual availability in Indonesia.

**Table 1.** Major Biomass Waste Resources in Indonesia

Biomass Source	Estimated Annual Availability (Million Tons/Year)
Palm Oil Waste (EFB, Shells, Fiber)	120-150
Rice Husk	12-15
Sugarcane Bagasse	8-10
Coconut Shell	3-5
Corn Residues	15-20
Forestry Residues	20-30
Municipal Organic Waste	25-35

The distribution of biomass resources across Indonesia is not uniform and largely reflects regional agricultural and industrial activities. Palm oil biomass is predominantly concentrated in major palm oil-producing provinces, particularly in Sumatra and Kalimantan. Among these regions, Riau Province has the highest concentration of oil palm plantations and palm oil processing facilities, making it one of the most promising locations for biomass-based hydrogen production. The province generates substantial quantities of empty fruit bunches, palm kernel shells, and other processing residues that can serve as feedstocks for hydrogen generation technologies.

North Sumatra also represents a major biomass-producing region due to its extensive palm oil industry and agricultural activities (Bruenig, 2016). The province hosts numerous palm oil mills and plantations, resulting in a continuous supply of biomass residues throughout the year. Furthermore,

North Sumatra benefits from relatively well-developed transportation and industrial infrastructure, which may facilitate the collection, transportation, and processing of biomass feedstocks for hydrogen production.

In Kalimantan, East Kalimantan has emerged as another strategic region with considerable biomass potential. In addition to oil palm residues, the province generates significant quantities of forestry residues from timber and wood-processing activities. These resources provide additional opportunities for biomass conversion technologies such as gasification and pyrolysis. The increasing focus on industrial development and renewable energy projects in East Kalimantan further enhances its attractiveness as a potential hub for green hydrogen production.

Beyond these regions, rice husk resources are primarily concentrated in major rice-producing provinces such as West Java, Central Java, East Java, and South Sulawesi (Octania, 2021). Sugarcane bagasse is mainly generated in East Java, Lampung, and Central Java, where sugar industries are concentrated. Coconut shell residues are abundant in North Sulawesi, Maluku, and several eastern Indonesian provinces that possess extensive coconut plantations. Meanwhile, municipal organic waste is generated throughout urban centers across the country, including Jakarta, Surabaya, Bandung, Medan, and Makassar.

The widespread availability of biomass resources across multiple sectors and geographic regions provides a strong foundation for the development of a biomass-based green hydrogen industry in Indonesia. The concentration of large biomass resources in provinces such as Riau, North Sumatra, and East Kalimantan offers particular advantages for establishing hydrogen production facilities due to reduced feedstock transportation requirements and improved supply chain efficiency. Consequently, these regions may serve as priority locations for future investments in biomass-to-hydrogen technologies and contribute significantly to Indonesia's transition toward a sustainable and low-carbon energy system.

### 3.2 Hydrogen Production Potential from Biomass Waste in Indonesia

The substantial availability of biomass waste in Indonesia provides significant opportunities for renewable hydrogen production. Through thermochemical and biological conversion technologies, biomass residues can be transformed into hydrogen, which serves as a clean energy carrier capable of supporting industrial decarbonization, power generation, transportation, and energy storage applications. The amount of hydrogen that can be produced depends on several factors, including feedstock characteristics, moisture content, carbon composition, conversion technology, and process efficiency.

Different biomass feedstocks exhibit varying hydrogen production yields due to differences in their lignocellulosic composition and energy content (Liu et al., 2018). Biomass residues with higher cellulose and hemicellulose contents generally produce larger quantities of hydrogen during gasification or reforming processes. In contrast, feedstocks with higher moisture content may require additional pretreatment, potentially reducing overall conversion efficiency. Based on values commonly reported in the literature, estimated hydrogen yields for major biomass resources in Indonesia are presented in Table 2.

**Table 2.** Estimated Hydrogen Yield from Major Biomass Feedstocks

Biomass Feedstock	Hydrogen Yield (kg H <sub>2</sub> /ton biomass)
Palm Oil Empty Fruit Bunches (EFB)	100-130
Palm Kernel Shells	70-100
Rice Husk	80-110
Sugarcane Bagasse	100-140
Coconut Shell	75-105
Corn Residues	85-120
Forestry Residues	50-90

The results indicate that coconut shells and palm kernel shells exhibit the highest theoretical hydrogen yields among the evaluated biomass resources. Their relatively high carbon content and low moisture levels make them particularly suitable for thermochemical conversion technologies such as gasification and steam reforming. Palm oil empty fruit bunches (EFB) also demonstrate considerable hydrogen production potential due to their abundant availability and favorable chemical composition. Although rice husks and municipal organic waste generally produce lower hydrogen

yields per unit mass, their large quantities and widespread distribution still make them important contributors to national hydrogen production.

To estimate the national hydrogen production potential, the annual biomass availability presented in the previous section was combined with biomass-specific hydrogen yields. Based on conservative assumptions regarding feedstock availability and conversion efficiency, Indonesia's biomass resources could theoretically generate millions of tons of hydrogen annually. Palm oil residues account for the largest share of this potential due to their overwhelming dominance in the national biomass inventory. Given an estimated availability of 120–150 million tons of palm oil waste per year and an average hydrogen yield of approximately 100 kg H<sub>2</sub> per ton of biomass, palm oil residues alone could potentially produce between 12 and 15 million tons of hydrogen annually.

Rice husks represent another significant resource, with annual production estimated at 12–15 million tons. Using average hydrogen yields of approximately 85 kg H<sub>2</sub> per ton, rice husk resources could contribute approximately 1.0–1.3 million tons of hydrogen per year. Similarly, sugarcane bagasse may generate approximately 0.7–1.0 million tons of hydrogen annually, while coconut shells could contribute between 0.3 and 0.6 million tons depending on feedstock availability and conversion efficiency. Forestry residues and municipal organic waste provide additional opportunities for hydrogen production, further increasing the national resource base.

The combined theoretical hydrogen production potential from Indonesia's major biomass resources is estimated to exceed 15 million tons of hydrogen per year under favorable utilization scenarios. This quantity represents a substantial renewable energy resource capable of contributing significantly to Indonesia's future energy demand. Considering that one kilogram of hydrogen contains approximately 33.3 kWh of energy, the estimated hydrogen potential corresponds to hundreds of terawatt-hours of renewable energy, highlighting its strategic importance for national energy security and decarbonization efforts.

Among all evaluated feedstocks, palm oil biomass emerges as the most promising resource for large-scale hydrogen production in Indonesia. This conclusion is supported by several factors. First, palm oil residues are available in exceptionally large quantities, particularly in major producing provinces such as Riau, North Sumatra, and East Kalimantan. Second, the continuous operation of palm oil mills ensures a stable and reliable feedstock supply throughout the year. Third, palm oil residues such as empty fruit bunches and palm kernel shells possess favorable physicochemical properties for thermochemical conversion processes. Finally, the existing infrastructure associated with the palm oil industry provides opportunities for integrating hydrogen production facilities with current biomass processing operations, thereby reducing transportation and logistics costs.

Coconut shells and palm kernel shells also demonstrate excellent hydrogen production characteristics due to their high carbon content and superior conversion efficiencies. However, their overall contribution to national hydrogen production is limited by lower feedstock availability compared to palm oil residues. Rice husks and sugarcane bagasse offer additional advantages because they are generated within well-established agricultural sectors and are geographically distributed across multiple regions, enabling decentralized hydrogen production systems.

### **3.3 Energy Potential of Biomass-Derived Hydrogen in Indonesia**

The estimated hydrogen production potential obtained from Indonesia's biomass resources represents a substantial renewable energy reserve that could contribute significantly to the country's long-term energy transition (Kelly-Yong et al., 2007). To better understand its practical implications, the hydrogen production potential can be converted into energy units commonly used in national energy planning, including kilowatt-hours (kWh), gigawatt-hours (GWh), and petajoules (PJ). Hydrogen possesses a high energy density, with approximately 33.3 kWh of energy contained in one kilogram of hydrogen based on its lower heating value (LHV).

Based on the previous estimation that Indonesia could theoretically produce more than 15 million tons of hydrogen annually from available biomass waste resources, the corresponding energy potential can be calculated (Ardebili, 2020). Assuming an average hydrogen production of 15 million tons (15 billion kilograms) per year, the total energy content would be approximately 499.5 billion kWh annually. This value is equivalent to approximately 499,500 GWh or nearly 1,798 PJ of renewable energy. These figures demonstrate the enormous energy potential embedded within

Indonesia's biomass waste resources and highlight their strategic importance for future energy development.

**Table 3.** Estimated Energy Potential of Biomass-Based Hydrogen in Indonesia

Parameter	Estimated Value
Hydrogen Production Potential	15 million tons/year
Energy Content	499.5 billion kWh/year
Equivalent Energy	499,500 GWh/year
Equivalent Energy	1,798 PJ/year

The estimated energy potential is particularly significant when compared with Indonesia's national electricity demand. In recent years, annual electricity consumption in Indonesia has been approximately 300–350 TWh (300,000–350,000 GWh). The theoretical energy potential of biomass-derived hydrogen, estimated at approximately 499,500 GWh annually, exceeds current national electricity consumption. Although not all hydrogen energy would be converted directly into electricity due to conversion losses and alternative applications, the comparison illustrates the substantial contribution that biomass-based hydrogen could make to the national energy system.

In addition to supporting electricity generation, green hydrogen has considerable potential for industrial applications (Oliveira et al., 2021). Indonesia's industrial sector consumes large quantities of energy for manufacturing, mineral processing, petrochemical production, fertilizer manufacturing, and transportation activities. Industries such as steel, cement, and chemical manufacturing are among the most energy-intensive sectors and remain heavily dependent on fossil fuels. Biomass-derived hydrogen could serve as a low-carbon alternative fuel and feedstock, enabling these industries to reduce greenhouse gas emissions while maintaining operational efficiency. Furthermore, hydrogen can be utilized in fuel cells, industrial heating processes, ammonia production, and synthetic fuel manufacturing, thereby expanding its role beyond conventional electricity generation.

The large-scale deployment of biomass-based hydrogen could also strengthen national energy security by reducing dependence on imported fossil fuels and diversifying Indonesia's energy portfolio (Abdul Malek et al., 2020). By converting locally available biomass waste into valuable energy products, the country can improve resource utilization while simultaneously promoting sustainable economic development. Consequently, biomass-derived hydrogen has the potential to become an important pillar of Indonesia's future low-carbon energy system.

Beyond its energy potential, the utilization of biomass waste for hydrogen production offers significant environmental benefits. One of the most important advantages is the reduction of waste accumulation from agricultural, forestry, agro-industrial, and municipal activities. Indonesia generates hundreds of millions of tons of biomass residues annually, much of which remains underutilized or is disposed of through environmentally harmful practices. Converting these residues into hydrogen creates value from waste materials while reducing environmental burdens associated with conventional disposal methods.

Waste reduction is particularly important because large quantities of agricultural residues are frequently burned in open fields or left to decompose naturally. Open burning releases particulate matter, carbon dioxide, methane, and other pollutants into the atmosphere, contributing to air quality degradation and climate change. Similarly, organic waste disposed of in landfills generates methane emissions through anaerobic decomposition. Methane is a potent greenhouse gas with a global warming potential significantly higher than carbon dioxide over a 100-year period. By redirecting biomass waste toward hydrogen production facilities, these emissions can be substantially reduced.

The implementation of biomass-to-hydrogen technologies can also decrease the volume of waste sent to landfills. Agricultural residues such as palm oil empty fruit bunches, rice husks, sugarcane bagasse, coconut shells, and forestry residues can be transformed into valuable energy resources rather than occupying landfill space (Kaniapan et al., 2021). This contributes to improved waste management practices and reduces the environmental impacts associated with landfill operations, including odor generation, leachate formation, and greenhouse gas emissions.

Another significant environmental benefit is the reduction of carbon emissions compared with conventional fossil fuel-based hydrogen production. Traditional hydrogen production methods, particularly steam methane reforming of natural gas, generate substantial carbon dioxide emissions. In contrast, biomass-based hydrogen production utilizes renewable carbon sources that are part of

the natural carbon cycle. The carbon released during hydrogen production is partially offset by carbon dioxide absorbed during biomass growth through photosynthesis, resulting in significantly lower net greenhouse gas emissions.

Furthermore, biomass-derived hydrogen supports the principles of the circular economy by transforming waste streams into valuable energy products. Instead of treating biomass residues as disposal challenges, they become renewable resources capable of generating economic and environmental benefits simultaneously. This approach improves resource efficiency, promotes sustainable production systems, and contributes to achieving national sustainability goals.

The environmental benefits are particularly relevant in regions with large concentrations of biomass waste, such as Riau, North Sumatra, and East Kalimantan (Simangunsong et al., 2017). In these provinces, hydrogen production facilities could help address waste management challenges associated with palm oil processing and forestry activities while simultaneously creating renewable energy resources. Consequently, the development of biomass-based hydrogen production can generate multiple environmental benefits, including waste reduction, lower landfill dependency, reduced greenhouse gas emissions, improved air quality, and enhanced resource sustainability.

### 3.4 Techno-Economic Feasibility of Biomass-Based Hydrogen Production in Indonesia

The successful deployment of biomass-based hydrogen technologies depends not only on resource availability and environmental benefits but also on economic viability. Although Indonesia possesses abundant biomass resources suitable for hydrogen production, the competitiveness of biomass-derived hydrogen is largely determined by production costs, technological efficiency, feedstock logistics, and infrastructure requirements. Therefore, a techno-economic assessment is essential to evaluate whether biomass-derived hydrogen can become a commercially viable alternative to conventional fossil fuel-based hydrogen.

One of the most important indicators in hydrogen economics is the production cost per kilogram of hydrogen (Kothari et al., 2008). Based on previous studies on biomass gasification, steam reforming, and biological conversion technologies, the production cost of biomass-derived hydrogen generally ranges from USD 2.0 to USD 6.0 per kilogram, depending on feedstock type, plant scale, conversion efficiency, and local operating conditions. Large-scale facilities utilizing abundant biomass feedstocks can achieve lower production costs due to economies of scale and reduced unit operating expenses. In contrast, small-scale facilities often experience higher production costs because capital and operating expenditures are distributed across lower production volumes.

**Table 4.** Estimated Hydrogen Production Costs by Production Pathway

Hydrogen Production Method	Estimated Cost (USD/kg H <sub>2</sub> )
Natural Gas Reforming (Grey Hydrogen)	1.0–2.0
Natural Gas Reforming with CCS (Blue Hydrogen)	1.5–3.0
Biomass Gasification	2.0–4.5
Biomass Steam Reforming	2.5–5.0
Biological Conversion	3.0–6.0
Renewable Electrolysis (Green Hydrogen)	3.5–8.0

The comparison indicates that natural gas-based hydrogen production remains the most economically competitive option in terms of direct production costs. Grey hydrogen produced through steam methane reforming typically costs between USD 1.0 and USD 2.0 per kilogram due to mature technology and well-established infrastructure. However, this pathway generates substantial carbon emissions and is increasingly challenged by global decarbonization policies. Blue hydrogen, which incorporates carbon capture and storage (CCS), exhibits moderately higher production costs but offers improved environmental performance.

Biomass-based hydrogen occupies an intermediate position between conventional fossil fuel-based hydrogen and renewable electrolysis-based hydrogen (Acar & Dincer, 2018). Although biomass-derived hydrogen generally costs more than grey hydrogen, it provides significant environmental advantages, including reduced greenhouse gas emissions and improved waste management. Furthermore, the utilization of low-cost biomass residues can substantially reduce feedstock expenses, particularly in regions with abundant agricultural and agro-industrial waste resources. Consequently, biomass-based hydrogen may become increasingly competitive as carbon

pricing mechanisms, emission regulations, and renewable energy incentives become more widespread.

The economic feasibility of biomass-derived hydrogen is strongly influenced by biomass transportation costs (Milne et al., 2002). Biomass resources are often geographically dispersed, requiring collection, handling, and transportation before processing. Transportation costs increase significantly when biomass feedstocks must be moved over long distances due to their relatively low energy density and bulky nature. Therefore, locating hydrogen production facilities near major biomass generation centers, such as palm oil processing regions in Riau, North Sumatra, and East Kalimantan, can substantially improve economic performance. Shorter transportation distances reduce logistical expenses and improve overall project profitability.

Another critical factor affecting hydrogen production costs is conversion technology efficiency. Higher conversion efficiencies result in greater hydrogen output from the same quantity of biomass, thereby reducing the unit production cost of hydrogen. Advanced gasification systems generally achieve higher efficiencies compared with biological conversion technologies, making them more attractive for large-scale commercial applications. Technological improvements in reactor design, catalyst performance, heat integration, and process optimization can further increase hydrogen yields while lowering operating costs (Ji et al., 2018). As biomass conversion technologies continue to mature, future cost reductions are expected through increased efficiency and improved system reliability.

Hydrogen storage and distribution infrastructure also represent significant cost components within the overall hydrogen value chain. Hydrogen has a low volumetric energy density under ambient conditions and therefore requires compression, liquefaction, or chemical storage to facilitate transportation and utilization. These processes require additional equipment, energy consumption, and capital investment. Storage systems such as high-pressure tanks, underground storage facilities, or hydrogen carriers can substantially increase project costs, particularly for large-scale hydrogen production facilities. Consequently, improvements in storage technologies and infrastructure development are essential for enhancing the economic competitiveness of biomass-derived hydrogen.

To further evaluate economic feasibility, a sensitivity analysis can be performed to identify variables with the greatest influence on hydrogen production costs. The analysis generally reveals that feedstock cost, transportation distance, conversion efficiency, and capital expenditure are the most sensitive parameters. For example, a 20% increase in biomass transportation costs may significantly raise the final hydrogen production cost, particularly in remote regions with limited infrastructure. Similarly, improvements in conversion efficiency can substantially reduce production costs by increasing hydrogen output without proportionally increasing operating expenses.

Capital expenditure is another major determinant of economic performance (Romp & De Haan, 2007). Hydrogen production facilities require investments in biomass preprocessing equipment, gasifiers or reactors, hydrogen purification systems, storage infrastructure, and supporting utilities. While initial investment requirements may be substantial, long-term economic performance can improve through economies of scale, technological learning, and government support mechanisms. Financial incentives, tax reductions, renewable energy subsidies, and carbon pricing policies can further enhance project attractiveness and accelerate commercialization.

### **3.5 Challenges and Barriers to Biomass-Based Hydrogen Development in Indonesia**

From a technical perspective, one of the primary challenges is the variability of biomass feedstocks. Biomass resources originate from diverse agricultural, forestry, and municipal sources, each possessing distinct physical and chemical characteristics. Variations in moisture content, ash composition, calorific value, cellulose content, and lignin concentration can significantly influence conversion performance and hydrogen yield. For example, palm oil empty fruit bunches, rice husks, sugarcane bagasse, and forestry residues exhibit different thermochemical properties, requiring specific pretreatment and processing conditions. Such variability complicates process standardization and may increase operational complexity and costs.

Another significant technical barrier relates to conversion efficiency (Tuller, 2017). Although technologies such as gasification, steam reforming, pyrolysis, and biological fermentation have demonstrated the ability to produce hydrogen from biomass, many systems still face efficiency

limitations. Energy losses during feedstock preparation, gas cleaning, hydrogen separation, and purification processes can reduce overall hydrogen output. Furthermore, biological conversion technologies generally exhibit lower hydrogen yields and longer processing times compared with thermochemical methods. Improving conversion efficiency through technological innovation, catalyst development, and process optimization remains a critical challenge for enhancing the competitiveness of biomass-based hydrogen production.

Economic barriers also represent a major obstacle to industry development (Frenkel, 2003). One of the most significant concerns is the high investment cost associated with hydrogen production facilities. Establishing a biomass-to-hydrogen plant requires substantial capital expenditure for feedstock preprocessing equipment, gasification or reforming units, hydrogen purification systems, storage facilities, and supporting infrastructure. These investment requirements are often considerably higher than those associated with conventional fossil fuel-based energy systems. Consequently, investors may perceive biomass-based hydrogen projects as financially risky, particularly in emerging markets where hydrogen demand remains relatively limited.

In addition to capital expenditure, operational costs can further affect project viability. Feedstock collection, transportation, labor, maintenance, and energy consumption contribute to the overall production cost of hydrogen. Although biomass waste is often considered a low-cost resource, logistical expenses can become substantial when feedstock sources are geographically dispersed. Without sufficient economies of scale and technological maturity, hydrogen production costs may remain less competitive than conventional fossil fuel alternatives.

Infrastructure limitations constitute another critical barrier to the development of a hydrogen economy in Indonesia (Nepal et al., 2021). Hydrogen storage remains a significant technical and economic challenge due to the low volumetric energy density of hydrogen under ambient conditions. Effective storage typically requires compression, liquefaction, or chemical carrier systems, all of which demand additional energy and specialized equipment. The high costs associated with storage infrastructure can significantly increase the overall cost of hydrogen deployment.

Transportation networks also require considerable development. Unlike conventional fuels, hydrogen distribution systems remain largely undeveloped in Indonesia. Dedicated hydrogen pipelines, refueling stations, storage terminals, and transportation facilities are currently limited or nonexistent in many regions. As a result, moving hydrogen from production sites to end users may involve substantial logistical challenges and additional expenses. Developing integrated hydrogen infrastructure will therefore be essential for supporting future market expansion and ensuring reliable supply chains.

Policy and regulatory barriers further influence the pace of hydrogen development (Dunn, 2002). Currently, Indonesia's regulatory framework for hydrogen remains relatively limited compared with more established renewable energy sectors. Specific standards governing hydrogen production, storage, transportation, safety, and utilization are still evolving. Regulatory uncertainty can discourage private investment and delay project implementation, particularly for large-scale infrastructure developments that require long-term planning and financial commitments.

Limited government incentives also represent a challenge for the commercialization of biomass-derived hydrogen. In many countries, hydrogen deployment is supported through subsidies, tax incentives, carbon pricing mechanisms, renewable energy credits, and research funding programs. Although Indonesia has demonstrated commitment to renewable energy development and carbon emission reduction, dedicated support mechanisms for hydrogen technologies remain relatively limited. Greater policy support could help reduce investment risks, improve project economics, and accelerate technology adoption.

Furthermore, market uncertainty remains an important consideration. Domestic demand for hydrogen is currently concentrated in specific industrial sectors such as fertilizer production and petroleum refining. The expansion of hydrogen utilization into transportation, power generation, and heavy industry will require significant investments in technology, infrastructure, and consumer adoption. Establishing stable demand and creating favorable market conditions are therefore essential for ensuring long-term industry growth.

Despite these challenges, the barriers identified are not insurmountable. Continuous technological advancement, strategic infrastructure development, supportive regulatory frameworks,

and targeted financial incentives can significantly improve the feasibility of biomass-based hydrogen production. Given Indonesia's abundant biomass resources and growing commitment to decarbonization, addressing these technical, economic, infrastructural, and policy challenges will be crucial for unlocking the full potential of biomass-derived hydrogen and supporting the country's transition toward a sustainable low-carbon energy future.

#### 4. CONCLUSION

This study demonstrates that Indonesia possesses substantial biomass waste resources that can serve as sustainable feedstocks for green hydrogen production. Among the various biomass sources evaluated, palm oil biomass, including empty fruit bunches, palm kernel shells, and other plantation residues, contributes the largest hydrogen production potential due to its abundant availability and favorable conversion characteristics. The findings indicate that significant quantities of hydrogen can be produced through thermochemical conversion technologies, particularly gasification and steam reforming, which offer high conversion efficiencies and technological maturity for large-scale implementation. Furthermore, the utilization of biomass-derived hydrogen provides important environmental benefits by reducing biomass waste accumulation, minimizing landfill disposal, lowering greenhouse gas emissions, and supporting national decarbonization efforts. These results suggest that biomass waste can become a strategic renewable energy resource capable of contributing to Indonesia's energy transition while enhancing resource efficiency and environmental sustainability. The development of a biomass-based hydrogen industry also has important implications for strengthening national energy security by diversifying energy sources, reducing dependence on fossil fuels, and utilizing locally available renewable resources. To realize this potential, several strategic actions are recommended, including the implementation of pilot-scale hydrogen production projects in biomass-rich regions, the provision of investment incentives and financial support mechanisms to attract private sector participation, the development and implementation of a comprehensive national hydrogen roadmap, and the conduct of further techno-economic, environmental, and life-cycle assessments to support evidence-based policymaking and commercial deployment. Overall, biomass-derived hydrogen represents a promising pathway for advancing Indonesia's sustainable energy future and achieving its long-term carbon reduction and energy security objectives.

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