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Integrated chemical looping gasification and steam reforming of palm oil waste for green hydrogen production in Indonesia: A comprehensive analysis and Aspen Plus simulation

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ABSTRACT

Background: Indonesia accounts for 42% of global palm oil production, generating 60 million tons of biomass waste per year, mainly empty fruit bunches and palm kernel shells that have strong potential to be converted into hydrogen (H_2) through biomass gasification as a renewable energy transition. This is relevant given that national hydrogen demand is projected to reach 6,282 TWh by 2060. Integrated chemical looping gasification technology with steam reforming using oxygen carrier $NiFe_2O_4$ shows promise for green hydrogen production from palm oil waste. **Methods:** This study was conducted through a literature review for comprehensive analysis and simulation data fulfillment. Process simulations were performed and analyzed using Aspen Plus, and sensitivity analysis was conducted for process optimization. **Findings:** Simulation results hydrogen production reaching 82.77 kg/hour at a gasification temperature of 700°C and a steam-to-biomass ratio of 0.9 with H_2 selectivity reaching 54.43%. Assessment of raw material quality and H_2 production quality revealed a material utilization rate of 12.08 tons per ton of H_2 produced. This simulation confirms the importance of optimizing the gasification temperature and steam-to-biomass ratio to produce high-quality syngas. PESTEL analysis shows that the use of palm oil waste for hydrogen has high economic value and creates a positive social impact. From a legal and environmental perspective, this conversion is in line with emission reduction regulations, making it feasible and highly implementable. **Conclusion:** Hydrogen production from palm oil waste using chemical looping gasification and steam reforming processes has significant potential for renewable energy in Indonesia. **Novelty/Originality of this article:** This study contributes by integrating technical, environmental, and socio-economic aspects in the analysis of hydrogen production from palm oil waste. Unlike most literature that focuses solely on process performance or technical aspects, this study combines Aspen Plus-based process simulation with PESTEL evaluation to assess the overall feasibility of the technology.

KEYWORDS: Aspen Plus simulation; gasification; green hydrogen; palm oil waste; renewable energy.

1. Introduction

Energy has always been a major issue in the world. With rapid technological advances, modern life has become increasingly dependent on energy, with a significant reliance on fossil fuels. In 2021, according to the World Energy Survey, oil and coal accounted for the majority of global energy consumption (She & Chen, 2025). In addition, the increase in

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world population, rising living standards, climate change, and global warming have exacerbated this issue. In 2023, world energy consumption reached 442 EJ (EJ), divided between industry (167 EJ), buildings (133 EJ), transportation (116 EJ), and other uses (27 EJ). This consumption is projected to reach 543.6 EJ by 2050 (Tavakoli et al., 2025). Furthermore, the high demand for fossil fuels as the main energy source has resulted in increased greenhouse gas emissions and energy vulnerability in many countries. However, these non-renewable resources pose environmental risks and will eventually be depleted.

Indonesia's oil and gas production will increase in 2030–2035 and will experience a significant decline from 2035 to 2060 (Ministry of Energy and Mineral Resources, 2025). This indicates the need for national energy diversification and transition efforts. One promising alternative energy source is hydrogen. Hydrogen has high energy density, clean combustion characteristics, and adaptability in various applications, making it a promising sustainable energy source. Hydrogen is a potential resource for achieving decarbonization targets in various industrial sectors (Shanmugasundaram et al., 2025). Hydrogen can be used as fuel for vehicles, power plants, and industrial raw materials. Hydrogen has several advantages, namely it is easy to store, is a carbon-free chemical, and can be used as an energy storage medium (IESR, 2022). Intensive research activities are underway, and many production and application pathways are being explored. Indonesia's oil and gas production for 2030–2035 as shown in Figure 1.

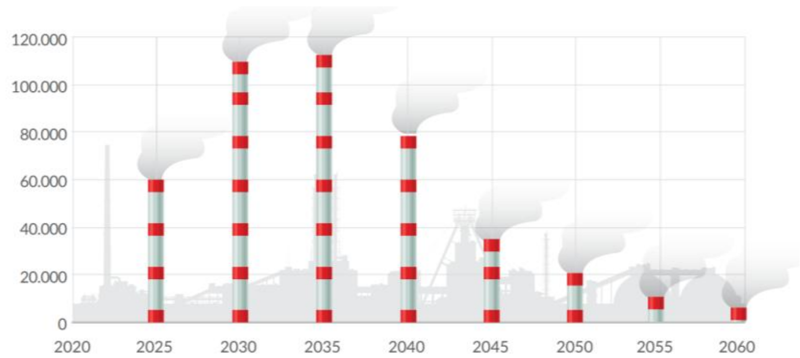

Fig. 1. Oil and gas production projections for 2020-2060
(Ministry of Energy and Mineral Resources, 2025)

According to the Ministry of Energy and Mineral Resources (2025), national hydrogen demand is projected to reach 6,282 TWh. The accumulation of hydrogen production and demand in Indonesia from 2025 to 2060 is presented in Figure 2. Domestic hydrogen production capacity is still far below demand because it still faces various challenges related to process efficiency, production costs, and high energy consumption (IESR, 2022). This condition indicates the need for efforts to improve hydrogen production technology. Hydrogen production can be carried out through several processes such as pyrolysis, electrolysis, and gasification. Given the need for hydrogen energy and environmental issues related to fossil fuels, the development of renewable energy alternatives in the form of green hydrogen sourced from sustainable raw materials, such as biomass, is crucial for a sustainable future. Biomass can be classified into wood and wood biomass, herbaceous biomass, aquatic biomass, and animal or human waste biomass. Organic materials, including municipal solid waste, sewage sludge, and industrial organic waste, such as black liquor from paper manufacturing, can also be considered biomass (Chen & Hsu, 2025). The palm oil industry represents a major potential source of biomass, as global production has increased from 8.3 million metric tons in 2000 to 43.5 million metric tons in 2020. Although palm oil contributes about 33 percent of global oils and fats production, approximately 90 percent of its output is generated as biomass waste, including empty fruit bunches, oil palm trunks, oil palm fronds, and palm kernel shells, which are often underutilized and pose environmental challenges due to uncontrolled decomposition and open burning. Therefore, the valorization of palm biomass into hydrogen represents a promising pathway for both waste management and renewable energy production (Kong et al., 2025).

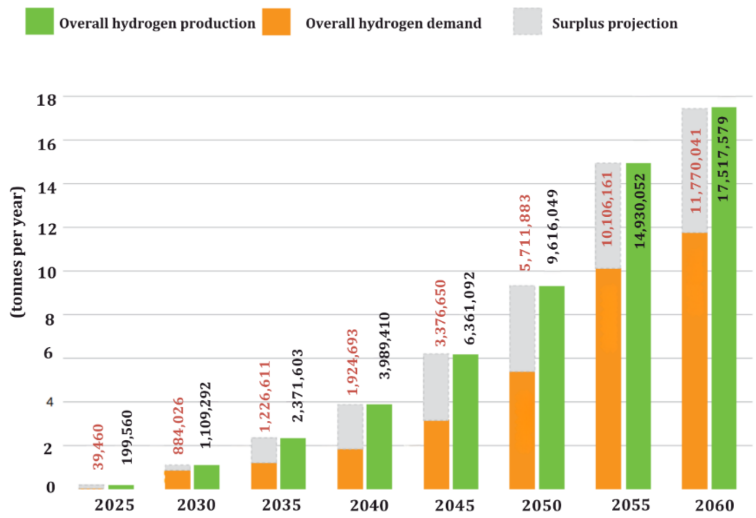

Fig. 2. Accumulation of hydrogen production and demand in Indonesia in 2025-2060 (Ministry of Energy and Mineral Resources, 2025)

Among various biomass conversion pathways, gasification is considered one of the most promising technologies for hydrogen production due to its ability to convert diverse biomass resources into synthesis gas with a high hydrogen content. Hydrogen production through biomass gasification is considered more optimal because it has a neutral carbon footprint, where CO_2 emissions released during the combustion process are offset by CO_2 previously absorbed by plants through photosynthesis. Gasification offers a dual-benefit approach to solving waste management problems and generating energy from various types of biomass waste, which is one of the most efficient technologies for converting waste into thermochemical energy (Ajorloo et al., 2025). Biomass gasification refers to the process of producing combustible syngas and solid-liquid waste through a series of redox reactions under specific thermodynamic conditions. This process is carried out using forestry waste, agricultural waste, domestic and industrial wastewater, and municipal waste as raw materials, and O_2, air, steam, CO_2, or a mixture of gases as gasification agents. In addition, this process also converts solid biomass fuel into combustible gas. The H_2 produced is the most valuable component of syngas, so finding a gasification method to produce H_2-rich syngas is essential. Biomass gasification in a reactor is a complex reaction involving many processes. It can generally be divided into drying, pyrolysis, oxidation, and reduction stages based on reaction temperature, and in reality, several stages can occur simultaneously in the reactor (Wang et al., 2026). Although recognized as an effective solution, gasification technology faces various challenges. These challenges include waste management, improving gasification efficiency, mitigating environmental impacts, and cost management. Traditional gasification methods show mediocre performance due to high energy consumption, low gas production rates, and other related problems. Better gasification technology is needed to develop a high-efficiency gasification approach that aims to improve overall efficiency.

To address these challenges, biomass chemical looping gasification has emerged as a promising alternative due to its high efficiency, economic feasibility, and low-emission characteristics. This process enabling the production of nitrogen-free synthesis gas while reducing dependence on costly air separation units. The process also benefits from the catalytic activity of oxygen carrier reduction products, which enhance tar cracking and reduce tar formation in the product gas. In addition, certain oxygen carriers can facilitate the conversion of ammonia and nitrogen oxide precursors into harmless nitrogen gas, thereby reducing harmful emissions. Biomass chemical looping gasification further offers an inherent carbon dioxide separation capability, making it a more sustainable option for synthesis gas and hydrogen production (Goel et al., 2026).

In this context, chemical looping gasification has emerged as a promising and practical technology for biomass conversion. Unlike conventional gasification, chemical looping gasification employs a recyclable oxygen carrier that transfers oxygen between the air reactor and fuel reactor without direct contact between air and fuel. This indirect oxidation mechanism improves syngas quality, enhances thermal efficiency, and reduces operational costs by minimizing the need for external oxygen supply. Among various oxygen carriers, $NiFe_2O_4$ has attracted considerable attention due to its excellent catalytic performance and reactivity. $NiFe_2O_4$ possesses an inverse spinel structure composed of Ni^{2+} and Fe^{3+} ions within a densely packed oxygen lattice. In this structure, Fe^{3+} ions preferentially occupy tetrahedral sites, promoting high oxygen mobility, efficient redox behavior, and strong catalytic activity during gasification. Furthermore, its ferromagnetic properties enable easier separation from solid fuel ash, thereby improving material recovery and process sustainability (Lin et al., 2020).

Based on these advantages, this study explores the potential utilization of palm oilbiomass waste as a raw material for green hydrogen production through the chemical looping gasification process with steam reforming, as well as the role of this technology in supporting national energy security. The purpose of this study is to analyze the potential utilization of palm oil waste as a renewable energy source, simulate and describe the chemical looping gasification with steam reforming process in green hydrogen production, and identify the opportunities and challenges of its implementation in Indonesia.

2. Methods

2.1 Literature review and process simulation modeling

The initial stage of the research was conducted through a literature study that included collecting data and information from scientific journals, textbooks, patents, and technical publications related to the process being studied. Initial data collection was carried out to assess the development of palm oil production and the availability of palm oil waste in Indonesia as a renewable raw material. The literature was also used to understand the basic principles of the process, reaction mechanisms, operating conditions, catalyst types, and relevant conversion and selectivity data. In addition, the literature study also served as the basis for determining assumptions, selecting thermodynamic models, and simulation parameters.

In the chemical looping gasification with steam reforming process simulation using Aspen Plus, the “General with metric units” template was used with “MIXCINC” selected to accommodate the simultaneous presence of conventional and non-conventional components. Empty palm fruit bunches and palm shells were used as raw materials in chemical looping gasification with steam reforming, categorized as non-conventional solids. To estimate the enthalpy and density of the material, the HCOALGEN and DCOALIGT thermophysical models were applied. The calculation of thermodynamic properties in this study utilizes the Peng-Robinson-Boston-Mathias (PR-BM) method for property estimation, using the Peng-Robinson equation of state with the Boston-Mathias α function. This model is well suited for gas processing in oil refining and related applications in coal processing, which include coal combustion, coal gasification, and coal liquefaction.

Given the unavailability of Gibbs free energy estimates for non-conventional components, DECOMP was used to decompose the feedstock into its elemental components, including H_2O, ash, S, O_2, N_2, H_2, and C. The RYIELD reactor calculated the distribution of component yields using FORTRAN to convert non-conventional components into conventional components. In addition, the ash fraction is considered a non-conventional solid, described as a component consisting exclusively of ash in a comprehensive analysis (Qi et al., 2024).

2.2 Model assumptions and equilibrium reactions

The gasification model used in this simulation is based on several key assumptions adapted from the study by Qi et al. (2024). To simplify the model while maintaining its ability to represent the major thermodynamic behavior of the gasification process, tar and other hydrocarbons are neglected, with the exception of methane (CH_4), which is retained because of its significant contribution to syngas composition in equilibrium gasification modeling. The gasification process is further assumed to operate under isothermal conditions, implying that the reactor temperature remains constant throughout the simulation. Although temperature gradients may occur in practical gasifiers and influence reaction kinetics as well as product distribution, this assumption simplifies the thermodynamic calculations without substantially affecting the equilibrium analysis. In addition, all sulfur-containing species are assumed to be completely converted into hydrogen sulfide (H_2S), while other sulfur compounds, such as sulfur dioxide (SO_2) and elemental sulfur, are excluded to reduce the complexity of the reaction network. Ash is treated as a non-conventional inert solid that does not participate in chemical reactions and is considered only in the overall mass balance of the system.

Table 1. Specific equilibrium reactions in Aspen Plus simulations

Reaction	Enthalpy	Reaction Name
Heterogenous reactions		
$C + H_2 \rightarrow CO_2$	-394 kJ/mol	Complete combustion
$C + CO_2 \rightleftharpoons 2CO$	+172 kJ/mol	Boudouard equilibrium
$C + H_2O \rightleftharpoons CO + H_2$	+131 kJ/mol	Water-gas
$C + 2H_2 \rightleftharpoons CH_4$	-75 kJ/mol	Methanation
Homogenous reactions		
$CO + 0.5O_2 \rightarrow CO_2$	-283 kJ/mol	CO partial combustion
$H_2 + 0.5O_2 \rightarrow H_2O$	-242 kJ/mol	H_2 combustion
$CO + H_2O \rightleftharpoons CO_2 + H_2$	-41 kJ/mol	CO shift
$CH_4 + H_2O \rightleftharpoons CO + 3H_2$	+206 kJ/mol	Steam-methane reforming
$CO_2 + CH_4 \rightarrow 2CO + 2H_2$	+246 kJ/mol	Dry reforming of methane
Hydrogen sulfide (H_2S) formation reaction		
$H_2 + S \rightarrow H_2S$		H_2S formation
Oxygen carrier reactions		
$Fe + H_2O \rightarrow FeO + H_2$	-92 kJ/mol	Steam oxidation of iron
$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$	+245 kJ/mol	Steam oxidation to magnetite
$NiFe_2O_4 \rightarrow Ni + 2Fe + 4[O]$	-964 kJ/kmol	Reduction of nickel ferrite

(Hoo & Said, 2021; Qi et al., 2024)

Furthermore, the simulation assumes that the gasification process is governed by thermodynamic equilibrium, meaning that all reactions proceed to completion and reach equilibrium composition at the reactor outlet. Nitrogen chemistry is also simplified by neglecting nitrogen oxides, with nitrogen assumed to react exclusively to form ammonia (NH_3) as the only nitrogen-containing product. Finally, the reaction mechanism of the oxygen carrier during the chemical looping gasification process cannot be explicitly represented in Aspen simulation. Therefore, the reduced state of the spinel-structured $NiFe_2O_4$ oxygen carrier is approximated as metallic Fe and Ni, while the lattice oxygen is represented as molecular oxygen (O_2). Accordingly, the oxygen carrier reactor is modeled through the decomposition of $NiFe_2O_4$ into Ni, Fe, and O_2. The specific reactions during the chemical looping gasification process with steam reforming for green hydrogen production in Aspen Plus simulation are presented in (Table 1).

2.3 Experimental data and materials and PESTEL analysis

In this modeling, raw materials in the form of empty palm fruit bunches and palm kernel shells used in the simulation process are classified as unconventional raw materials and their characteristics are determined through ultimate analysis, which reveals their elemental composition, and proximate analysis, which identifies their constituent components. The data from the ultimate analysis and proximate analysis refer to the research by Kong et al. (2025), which provides detailed values for the characteristics of empty palm fruit bunches and palm kernel shells.

PESTEL analysis is used to identify strengths, weaknesses, opportunities, and threats. This study focuses on the use of palm oil waste (empty palm fruit bunches and palm kernel shells) in the development of green hydrogen renewable energy with chemical looping gasification technology integrated with steam reforming. Based on the findings from various documents or literature used, several impacts have been listed, including economic, social, environmental, and technological, among others. To examine this in more detail, the PESTEL approach was considered because it helps provide a better understanding of the current external influences affecting the development of green hydrogen renewable energy from palm oil waste, helping to identify factors that may change, reduce risks, and take advantage of opportunities needed to remain competitive and develop better long-term strategies. In addition, the use of this framework makes it possible to closely observe the impact of the development of green hydrogen renewable energy from palm oil waste based on the political, economic, social, technological, legal, and environmental factors that influence it and provides a comprehensive framework for addressing the sustainability challenges faced by the energy sector in Indonesia (Kansongue et al., 2023). Based on the results of the literature review, there are important factors that influence the development of renewable energy, such as political, economic, social, technological, legal, and environmental factors.

3. Results and Discussion

3.1 The potential of empty palm fruit bunches and palm shells in Indonesia

Based on data from Statistics Indonesia 2023 by BPS (2024), the area of palm oil plantations based on land use and crude palm oil (CPO) production in 2018 increased significantly compared to previous years. This increase was due to the expansion of the administrative coverage of palm oil companies, resulting in a palm oil plantation area of 14.33 million hectares. Subsequently, from 2019 to 2023, the palm oil plantation area based on land use continued to increase at a nearly stagnant rate. In 2023, the area of oil palm plantations is estimated to be 15.93 million hectares. Oil palm plantation areas are spread across 26 provinces, namely all provinces on the islands of Sumatra and Kalimantan, West Java, Banten, Central Sulawesi, South Sulawesi, Southeast Sulawesi, West Sulawesi, Gorontalo, Maluku, North Maluku, Papua, and West Papua. The data on the ten provinces in Indonesia with the largest oil palm plantation areas in 2023 is presented in Table 2.

Table 2. Area of Indonesia oil palm by province and category of producers (ha) in 2023

Province	Area (ha)				
	Government estates	Private estates	Smallholders	Area to be confirmed	Total area of land cover
Riau	75,540	1,037,482	2,288,586	92,976	3,494,583
Kalimantan Tengah	–	1,772,908	398,093	-133,295	2,037,705
Sumatera Utara	320,225	534,804	497,197	666,502	2,018,727
Kalimantan Barat	27,848	1,448,019	657,545	-303,879	1,829,533
Sumatera Selatan	25,097	667,155	548,838	166,454	1,407,544
Kalimantan Timur	15,756	1,255,049	220,145	-169,258	1,321,692
Jambi	28,648	277,796	645,706	238,663	1,190,813
Aceh	28,648	277,796	645,706	238,663	1,190,813
Sumatera Barat	8,403	177,911	253,962	114,800	555,076
Kalimantan Selatan	5,377	354,570	110,788	45,297	516,033
Indonesia	577,937	8,614,259	6,736,516	905,273	16,833,985

(BPS, 2024)

In 2023, Riau Province remained the largest palm oil producing province with an area of 3.40 million hectares or 21.36 percent of the total palm oil plantation area in Indonesia. Regarding palm oil production data in Indonesia, in 2022 there was an increase of 3.76 percent compared to 2021 to 46.82 million tons. In 2023, CPO production increased again to 47.08 million tons. The largest palm oil (CPO) production in 2023 came from Riau Province with a production of 9.22 million tons, or around 19.59 percent of Indonesia's total production. Data on the total area and production of oil palm in Indonesia from 2019 to 2023 are presented in (Fig. 3).

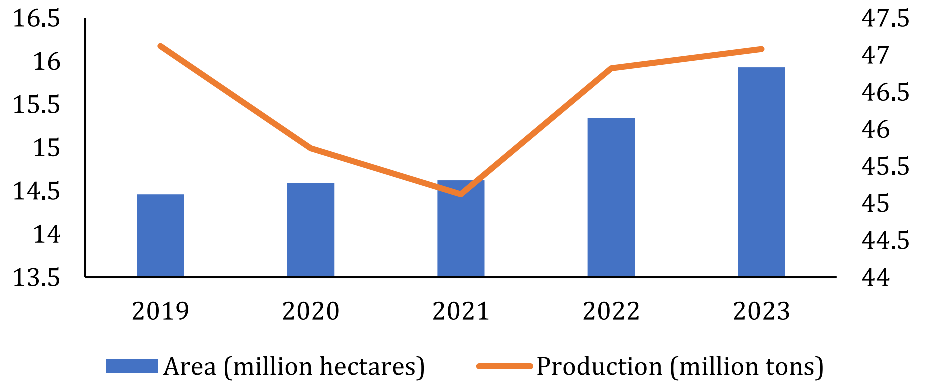

Fig. 3. Area and Production of Indonesia Oil Palm, 2019–2023
(BPS, 2024)

However, crude palm oil accounts for only about 10% of total production, while 90% of palm biomass is treated as waste (Kong et al., 2025). Approximately 60 million tons of waste are generated from the palm oil industry each year (Waluyo & Rauf, 2024). More specifically, Ilhami et al. (2024) projected that biomass production, such as empty palm fruit bunches and palm kernel shells, would reach 74.5 tons per hectare per year, indicating abundant availability each year, making it an ideal and sustainable raw material.

Empty palm fruit bunches and palm kernel shells stand out from other palm oil waste in terms of availability and characteristics. Processing one ton of fresh palm fruit bunches produces 235 kg of empty palm fruit bunches and 70 kg of palm kernel shell waste. In addition to their availability, the characteristics of empty palm fruit bunches and palm kernel shells are very promising for hydrogen production. The characteristics of empty palm fruit bunches and palm kernel shells in the form of proximate analysis and ultimate analysis are presented in Table 3.

Table 3. Characteristics of empty palm fruit bunches and palm kernel shells

Parameters	Empty palm fruit bunch	Palm kernel shells
Proximate analysis (wt.%)		
Moisture	2.42	4.17
Volatile matter	73.16	66.40
Fixed carbon	19.24	24.70
Ash	5.17	4.73
Ultimate analysis (wt.%)		
Carbon	39.60	42.71
Hydrogen	5.00	5.26
Nitrogen	1.47	0.41
Sulfur	1.38	0.85
Ash	5.17	4.73
Oxygen	47.38	46.04

(Kong et al., 2025)

In addition to its availability, the characteristics of empty palm fruit bunches and palm shells are highly promising for hydrogen production. Palm kernel shells have a high hydrogen content of 5.56% compared to empty palm fruit bunches with a hydrogen content of 5%; thus, palm kernel shells are more promising in terms of the hydrogen energy yield from gasification. However, it should be noted that the high moisture content in palm kernel shells can reduce the efficiency of the process and may require special treatment before gasification, such as drying. The volatile matter content of palm kernel shells is 66.40%, which is lower than that of empty palm fruit bunches, which have a very high volatile matter content of 73.16%. This shows that empty palm fruit bunches have the highest potential for producing volatile substances during pyrolysis, while palm kernel shells, with their lower volatile substance content, exhibit greater thermal stability. The high volatile matter content indicates that this raw material is flammable and can react quickly during combustion. The ash content is 5.17% by weight in empty palm fruit bunches and 4.73% by weight in palm kernel shells. The ash content in these biomasses is low enough to support cleaner thermochemical processing. In addition, the high carbon content also increases the thermal efficiency of the process. The oxygen content in both biomasses is high, at more than 46% by weight in empty palm fruit bunches and palm kernel shells. This high oxygen level reduces the need for additional air during combustion, highlighting its potential as an economically viable and sustainable fuel source (Kong et al., 2025). Thus, the combination of empty palm fruit bunches and palm kernel shells as raw materials or biomass has strong potential for green hydrogen production.

3.2 Chemical looping gasification with steam reforming process

Chemical looping gasification with steam reforming is a gasification technology that uses oxygen carriers (OC) and steam. The chemical looping gasification process highlights a substantial increase in biomass conversion efficiency facilitated by the presence of H_2O. In this methodology, H_2O not only functions as a gasification agent but also contributes lattice oxygen to oxygen carriers for H_2 production. The main objective of chemical looping gasification is to produce hydrogen and syngas for various downstream chemical processes. Since the introduction of chemical looping technology, many researchers have modeled and simulated the chemical looping gasification process to assess the impact of various operating conditions on gasification (Qi et al., 2024).

The chemical looping gasification process with steam reforming significantly increases H_2 production, which is widely used in the chemical industry and in clean energy production. The chemical looping gasification system with steam reforming involves three reactors for gasification, steam reforming, and oxygen carrier reoxidation. The gasification reactor converts biomass into syngas, and oxygen carrier is reduced through the following reaction. Then, oxygen carrier enters the steam reactor, where oxidation of H_2O produces H_2-rich syngas. Finally, calcination of oxygen carrier in the water reactor completes the oxidation recovery of oxygen carrier (Lin et al., 2020; Qi et al., 2024).

$$C_nH_mO_x \text{ (biomass)} \rightarrow \text{char} + \text{syngas } (CO, H_2, H_2O, CO_2, CH_4)$$
$$NiFe_2O_4 \rightarrow Ni + 2Fe + 4[O] \quad \text{(Eq. 1)}$$

$$Fe + H_2O \rightarrow FeO + H_2$$
$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2 \quad \text{(Eq. 2)}$$

3.3 Aspen Plus process simulation

The biomass chemical looping gasification with steam reforming process was simulated using Aspen Plus to evaluate syngas composition and hydrogen production performance under various operating conditions. The simulation model was developed based on thermodynamic equilibrium principles and process configurations adapted from Qi et al. (2024). Since no previous study has specifically investigated the utilization of mixed empty fruit bunches and palm kernel shells with $NiFe_2O_4$ oxygen carrier in an integrated chemical looping gasification–steam reforming system, model validation was conducted using published biomass gasification and chemical looping gasification studies with comparable operating conditions and equilibrium-based simulation approaches. Key syngas components, including H_2, CO, CO_2 and CH_4, were compared with literature data to evaluate the reliability of the developed model. The comparison results presented in (Table 4) indicate good agreement between the simulation results and published studies, demonstrating that the developed Aspen Plus model is capable of reasonably predicting syngas composition and hydrogen production behavior.

Table 4. Comparison of simulation results and literature data for model validation

Component	Gas composition (mol. %)		
	Empty palm fruit bunch	Palm kernel shells	This study
Hydrogen	47 – 55	40 – 50	49.13 – 55.40
Carbon monoxide	8 – 20	15 – 30	0.57 – 9.44
Carbon dioxide	30 – 45	20 – 35	38.82 – 44.10
Methane	0 – 3	0 – 3	0.00 – 2.68

(Anyaoha et al., 2020; Chuayboon & Abanades, 2023)

The results in Table 4 show that the simulation outcomes are generally in good agreement with literature data for both empty fruit bunches and palm kernel shells, indicating that the developed Aspen Plus model is reliable. The hydrogen yield (49.13–55.40 mol%) falls within or slightly above the reported ranges, which can be attributed to the thermodynamic equilibrium assumption that tends to predict an ideal maximum conversion. Carbon dioxide levels (38.82–44.10 mol%) are also consistent with literature trends, while methane remains low (0.00–2.68 mol%) as expected under high-temperature conditions. However, the carbon monoxide content (0.57–9.44 mol%) is relatively lower, likely due to enhanced conversion to hydrogen and carbon dioxide under equilibrium conditions. Despite this agreement, the model is still limited by equilibrium assumptions that neglect kinetic effects and real reactor non-idealities, meaning that further experimental validation is needed for more accurate practical prediction.

Following the validation process, the chemical looping gasification with steam reforming system was simulated using a biomass feed rate of 1,000 kg/h consisting of 50% empty fruit bunches and 50% palm kernel shells, with a constant oxygen carrier flow rate of 300 kg/h. The process configuration employed in this study was adapted from the design proposed by Qi et al. (2024) with several modifications to accommodate the selected biomass composition and operating conditions. The resulting process flow diagram generated using Aspen Plus is presented in (Fig. 4).

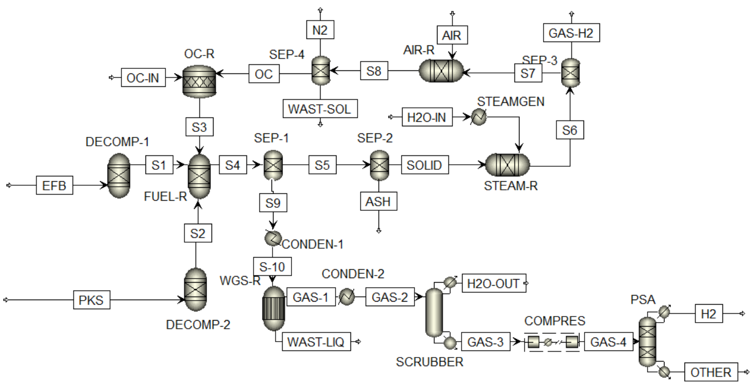

Fig. 4. Aspen Plus simulation results

The description of the Aspen Plus reactor blocks and illustration of the process flow diagram are given in (Table 5). The oxygen carrier (OC) plays a key role by providing lattice oxygen and facilitating reduction reactions. SEP-1 is responsible for effectively separating reaction products into solid constituents, including ash content and reductive OC. SEP-2 is used to extract ash from the solid phase component, after which the reduced OC proceeds to STEAM-R for initial oxidation reactions. This initial oxidation is aided by steam, which provides the necessary lattice oxygen and contributes to additional H_2 decomposition. The SEP-3 unit is tasked with efficiently separating and collecting the H_2 produced. The SEP-4 unit is tasked with separating waste oxygen carrier. Directed to AIR-R, the partially oxidized OC achieves full oxidation to $NiFe_2O_4$, enabling the OC cyclic process between STEAM-R, AIR-R, and FUEL-R. Gas from SEP-1 undergoes a water gas shift reaction in WGS-R, thereby increasing syngas production. To further purify the gas, a scrubber is used to condense the steam into water and separate it from the remaining gas. The final step involves gas precipitation with pressure swing adsorption (PSA) to produce pure H_2. In the Aspen Plus model, OC is reduced to a lower oxidation level. Inside FUEL-R, OC is then transported through STEAM-R to AIR-R. In AIR-R, OC is heated by an external reactor via electric heating, allowing it to carry heat back to FUEL-R. This heat transfer supports the partial oxidation reaction inside FUEL-R, maintaining the high-temperature environment essential for efficient gasification. Thus, the cyclic movement of OC between FUEL-R and AIR-R ensures both oxygen transfer and heat circulation within the system, significantly improving overall energy efficiency (Qi et al., 2024).

Table 5. Description of the reactor blocks used in the simulation model

Block name	Aspen Plus name	Spesifications		Description
DECOMP-1	RYield	Temperature Pressure	500°C 0.1 MPa	Transformation of non-conventional components (empty palm fruit bunches) into standard components through elemental analysis.
DECOMP-2	RYield	Temperature Pressure	500°C 0.1 MPa	Transformation of non-conventional components (palm kernel shells) into standard components through elemental analysis.
FUEL-R	RGibbs	Temperature Pressure	600-1000°C 0.1 MPa	Modeling of gasification reactions based on Gibbs free energy principles.
STEAM-R	RGibbs	Temperature Pressure	750°C 0.1 MPa	Supplying oxygen carrier with oxygen.
AIR-R	RGibbs	Temperature Pressure	700°C 0.1 MPa	Supplying oxygen carrier with oxygen.
WGS-R	REquil	Pressure Duty	0.1 Mpa 0 kW	Simulation of water gas shift reaction.
OC-R	RStoic	Temperature Pressure	720°C 0.1 MPa	Inducing reduction reactions in oxygen carrier.
SEP-1 SEP-2 SEP-3 SEP-4	Sep			Isolating targeted streams from mixed streams.
CONDEN-1	Heater	Temperature Pressure	350°C 0.1 MPa	Condensing gas.
CONDEN-2		Temperature Pressure	150°C 0.1 MPa	
STEAMGEN	Heater	Temperature Pressure	250°C 0.1 MPa	Transforming liquid phase into gas phase.
SCRUBBER	Sep			Simulating H_2O separation from product gas for recovery.
COMPRES	MCompr	Stages Fix discharge pressure from last stage	1 1 MPa	Simulating compressors.
PSA	Sep			Modeling H_2 extraction from gas mixtures.

3.4 Sensitivity analysis: Simultaneous effect of gasification temperature and steam-to-biomass mass ratio

Sensitivity analysis was performed to evaluate the simultaneous effect of gasification temperature and steam-to-biomass mass ratio on the selectivity of synthesis gas components, including H_2, CO, CO_2, and CH_4. These two parameters were selected as the main operating variables because they strongly govern reaction equilibrium, gas-phase reaction pathways, and overall syngas composition in biomass gasification systems. The gasification temperature range of 600–1000°C was chosen based on typical operating conditions reported in biomass and chemical looping gasification studies, where lower temperatures tend to favor incomplete conversion and methane formation, while higher temperatures promote endothermic reactions such as steam reforming and water–gas shift reactions, leading to increased hydrogen production. In addition, the steam-to-biomass mass ratio range of 0.5–2.1 was selected to represent conditions from steam-deficient to steam-rich environments, where lower ratios may limit hydrogen formation due to insufficient steam availability, whereas higher ratios enhance hydrogen yield but may increase energy demand for steam generation and affect syngas concentration. The results of the sensitivity analysis are presented in (Fig. 5), which illustrates contour maps of gas selectivity as a function of gasification temperature and steam-to-biomass ratio.

Based on the simulation results, hydrogen (H_2) selectivity tends to increase with increasing gasification temperature and steam: biomass ratio. At low temperatures (around 600–700°C), H_2 selectivity is very sensitive to changes in the steam-to-biomass ratio. This is due to the dominance of the water–gas shift reaction and the steam reforming reaction of light hydrocarbons, which require a sufficient amount of water vapor. An increase in the steam ratio accelerates the equilibrium shift towards H_2 formation, resulting in a higher hydrogen fraction in the syngas. This phenomenon is consistent with the literature by Qi et al. (2024), which reports that at low temperatures, the contribution of water vapor to H_2 formation becomes more significant than the effect of temperature itself. This effect is even more pronounced in biomass feedstocks with high water vapor content (Jiang et al., 2023).

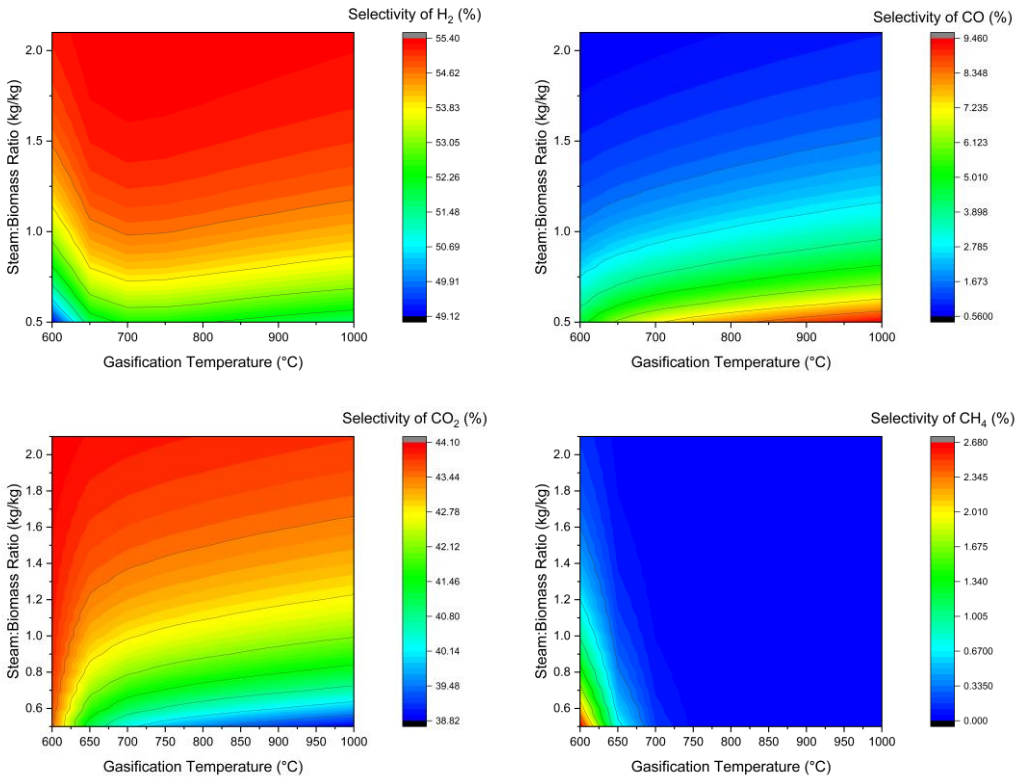

Fig. 5. Sensitivity analysis of chemical looping gasification with steam reforming

Meanwhile, methane (CH_4) selectivity shows very low values at high temperatures and large steam ratios. CH_4 tends to form at low temperatures through the methanation reaction, but decomposes at high temperatures due to steam reforming and thermal cracking reactions (Adnan et al., 2022). These results confirm that increasing the temperature and steam ratio effectively suppresses CH_4 formation, thereby improving the quality of syngas for advanced energy applications. Overall, increasing the steam-to-biomass ratio contributes positively to improving the quality of combustible gas through increased H_2 selectivity and reduced saturated hydrocarbon fractions, as also reported by Qi et al. (2025). This simulation confirms the importance of simultaneously optimizing gasification temperature and steam-to-biomass ratio to produce high-quality syngas tailored to specific applications such as hydrogen production or synthetic fuels (Bauer et al., 2023).

3.5 Energy efficiency of chemical looping gasification with steam reforming

The integration of Chemical Looping Gasification (CLG) technology with Steam Reforming (SR) results in a significant increase in energy efficiency. Thermodynamic analysis shows that the overall energy efficiency of this integrated system reaches 55.24%. Technically, the system requires a net input power of 603.72 kW to run its cycle. The main advantage that drives this high efficiency is the role of the oxygen carrier, which facilitates effective internal heat exchange between the water reactor (where exothermic oxidation reactions occur) and the fuel reactor (where endothermic reduction occurs). This mechanism minimizes energy loss and optimizes heat utilization in the process, unlike conventional gasification systems, which often experience significant heat loss due to the need for external heating (Wu et al., 2020). This improvement is particularly evident when compared to chemical looping gasification systems without steam reforming integration, which only have an energy efficiency of around 35% (Hantoko et al., 2025).

Thus, Steam reforming integration not only increases hydrogen yield but also fundamentally improves the thermal performance of the entire system. Further optimization of the steam-to-biomass ratio and selection of oxygen carriers with high specific heat capacity and optimal thermal conductivity can drive efficiency close to 60% (Qi et al., 2024). These simulations confirm that the integrated chemical looping gasification and steam reforming approach is a promising technological solution for energy-efficient and sustainable green hydrogen production.

3.6 Emissions control analysis

Green hydrogen is projected to be a key catalyst in the global energy transition, offering solutions for decarbonizing hard-to-abate sectors. An analysis by the Ministry of Energy and Mineral Resources (2025) indicates substantial potential for carbon emission reductions, with green hydrogen globally reducing 3.7–6.0 gigatons of CO_2-equivalent per year by 2050, equivalent to about 10% of current total global anthropogenic emissions. This contribution will mainly be supported by its role in heavy industry; substituting fossil fuel-based processes with green hydrogen in sectors such as steel, cement, chemicals, and heavy transport has the potential to cut emissions by up to 2.3 gigatons of CO_2 per year (IEA, 2023). At the national level, the development of Indonesia's green hydrogen industry is expected to contribute directly to the achievement of the Nationally Determined Contribution (NDC) target by mitigating up to 126 million tons of CO_2 by 2060 (Ministry of Energy and Mineral Resources, 2025).

3.7 Economic feasibility projections

Economic feasibility projections indicate that green hydrogen production in Indonesia will become increasingly competitive in the coming decade. According to an analysis by the Ministry of Energy and Mineral Resources (2025), in 2023 the price of green hydrogen will still be relatively high, ranging from US$10–11/kg, mainly due to the cost of initial technology investment and limited production scale. However, with technological advances, increased production scale, and consistent policy support, the price is projected to drop significantly to US$4–6/kg by 2030. This decline is in line with the global trend, where green hydrogen production costs are expected to fall by up to 50% over the same period, mainly due to economies of scale and increased process efficiency (IRENA, 2023). Thus, chemical looping gasification and steam reforming technologies not only offer technical and environmental advantages but also have high potential to make green hydrogen an economically viable and competitive renewable energy source in the global market. This cost advantage can accelerate the adoption of green hydrogen in strategic sectors such as industry, heavy transportation, and power generation, while strengthening Indonesia's position as a major player in the regional green hydrogen supply chain (IEA, 2024).

3.8 Politics, economy, society, technology, environment, law (PESTEL) analysis

A PESTEL analysis of the development of green hydrogen from palm oil waste (empty palm fruit bunches and palm shells) using chemical looping gasification with steam reforming technology in Indonesia shows strategic potential in various aspects. From a political perspective, the development of green hydrogen has received strong commitment from the Indonesian government in achieving its 2060 Net Zero Emission (NZE) target and diversifying the national energy mix. This commitment is outlined in strategic documents such as the National Energy General Plan and the hydrogen roadmap (Ministry of Energy and Mineral Resources, 2025). The government plays a key role in creating a conducive investment climate through supportive regulations and fiscal incentives, such as tax allowances for green technologies. However, such projects are not immune to the risks of political dynamics and changes in government priorities. On the other hand, the global momentum for energy transition opens up opportunities for international cooperation, especially with countries such as Japan and South Korea that are actively seeking green hydrogen supplies, thereby attracting foreign investment and technology transfer.

Economically, the integration of chemical looping gasification with steam reforming for hydrogen production from palm oil waste promises a cost advantage. Techno-economic studies show that this technology can achieve a competitive Levelized Cost of Hydrogen (LCOH). The simulation results show a potential LCOH of US$ 2,487/kg H_2, which is lower than several other green hydrogen production routes because it utilizes low-cost waste raw materials (Qi et al., 2024). Additionally, this technology creates a new circular economy by transforming the cost burden of waste management into a revenue stream, while increasing added value for the palm oil industry. Investment in such projects has the potential to create jobs in construction, operations, and research. The main challenge lies in the high initial capital expenditure (CAPEX) required for facility construction and technology mastery, which necessitates fiscal incentives or innovative financing schemes to attract private investors (Ishaq & Dincer, 2020).

Social acceptance is a fairly important factor. On the one hand, growing public awareness of climate change and waste pollution encourages support for environmentally friendly technologies. This project can improve the image of the palm oil industry by offering solutions to its waste problems, while also potentially create employment opportunities in rural and urban areas. Jobs may be generated in biomass cultivation, harvesting, transportation, and the operation and maintenance of biomass energy facilities (Erdiwansyah et al., 2024). On the other hand, effective communication and education are needed to inform the public about the safety and benefits of this new technology, given that hydrogen and gasification plants may be perceived as risky. Community engagement from the planning stage is essential to build trust and ensure that socio-economic benefits are distributed fairly.

In terms of technology, the integration of chemical looping gasification with steam reforming and the use of oxygen carriers such as $NiFe_2O_4$ shows promising energy efficiency (>55%) with low carbon emissions. This technology is a breakthrough in converting solid waste into clean energy. However, this technology is still at the pilot plant or small-scale demonstration stage in many countries, so its commercial application in Indonesia carries technical risks and requires adaptation. The environmental impact of this technology is very positive and aligns with the principles of the circular economy. Every 1 ton of green hydrogen produced can utilize around 12.08 tons of palm oil waste, thereby significantly reducing the volume of solid waste disposed of in landfills or burned in open fires, which contributes to reduce the bulk, and to curb emissions of Greenhouse gas while producing value (Awoh et al., 2023). The chemical looping gasification process inherently produces a relatively pure CO_2 gas stream, which is ideal for Carbon Capture, Utilization, and Storage (CCUS) applications, thus potentially achieving negative emissions. As such, this technology makes a double contribution to climate change mitigation by reducing emissions from waste management and producing clean energy to replace fossil fuels.

Legally, Indonesia has a fundamental basis through Law No. 30 of 2007 concerning Energy, which regulates national energy management, including the development of new and renewable energy. This foundation is reinforced by commitments in Law No. 11 of 2020 concerning Job Creation and Presidential Regulation No. 112 of 2022 concerning the Acceleration of Renewable Energy Development. This framework serves as a foundation, but the implementation of specific technologies such as the integration of chemical looping gasification and steam reforming requires legal regulations as a further technical and operational basis.

4. Conclusions

Based on a comprehensive analysis, the integration of chemical looping gasification technology with steam reforming for converting palm oil solid waste (empty fruit bunches and palm kernel shells) demonstrates strong potential as a green hydrogen production pathway for Indonesia. This process achieves hydrogen production with high energy efficiency (>55%) and hydrogen selectivity exceeding 50%, while contributing to reduced carbon emissions through effective waste utilization and the inherently low-carbon nature of the process. From an economic perspective, the estimated production cost of around US$ 2,487/kg H_2 indicates potential competitiveness compared to conventional methods, particularly due to the availability of abundant and low-cost biomass feedstock. However, these results are obtained from simulation based on thermodynamic equilibrium assumptions, which do not fully capture kinetic limitations and real reactor non-idealities, indicating the need for further experimental validation to support industrial application.

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Author Contribution

M.I.N., conceptualization, methodology, data collection, simulation analysis, visualization and writing–original draft. D.W.A.A., literatur reviewer, conceptualization, PESTEL analysis, and writing–review and editing.

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During the preparation of this work, the authors used Grammarly, and DeepL to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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References

Adnan, M. A., Xiong, Q., & Muraza, O. (2022). A comprehensive review on the factors affecting thermochemical conversion efficiency of algal biomass to energy. *Science of The Total Environment, 806*, 150565. https://doi.org/10.1016/j.scitotenv.2021.150565

Ajorloo, M., Ghodrat, M., Scott, J., & Strezov, V. (2025). Evaluating the role of feedstock composition and component interactions on biomass gasification. *Fuel, 381*, 133528. https://doi.org/10.1016/j.fuel.2024.133528

Anyaoha, K. E., Sakrabani, R., Patchigolla, K., & Mouazen, A. M. (2020). Co-gasification of oil palm biomass in a pilot scale downdraft gasifier. *Energy Reports, 6*, 1888-1896. https://doi.org/10.1016/j.egyr.2020.07.009

Awoh, E. T., Kiplagat, J., Kimutai, S. K., & Mecha, A. C. (2023). Current trends in palm oil waste management: A comparative review of Cameroon and Malaysia. *Heliyon*, *9*(11). https://doi.org/10.1016/j.heliyon.2023.e21410

BPS. (2024). *Statistik Kelapa Sawit Indonesia 2023*. Badan Pusat Statistik. https://www.bps.go.id/id/publication/2024/11/29/d5dcb42ab730df1be4339c34/statistik-kelapa-sawit-indonesia-2023.html

Bauer, C., Treyer, K., Heck, T., & Zhang, X. (2023). On the climate impacts of blue and green hydrogen: A comprehensive system perspective. *International Journal of Hydrogen Energy, 48*(52), 19900-19919. https://doi.org/10.1016/j.ijhydene.2023.02.088

Chen, G. B., & Hsu, Y. T. (2025). ASPEN Plus simulation of palm kernel shells, waste shiitake substrate, and sewage sludge co-gasification. *Energy, 329*, 136820. https://doi.org/10.1016/j.energy.2025.136820

Chuayboon, S., & Abanades, S. (2023). Carbon-neutral synfuel production via continuous solar H_2O and CO_2 gasification of oil palm empty fruit bunch. *Energy, 281*, 128212. https://doi.org/10.1016/j.energy.2023.128212

Erdiwansyah, Gani, A., Mamat, R., Nizar, M., Yana, S., Yasin, M. H. M., & Rosdi, S. M. (2024). Prospects for renewable energy sources from biomass waste in Indonesia. *Case Studies* *in Chemical and Environmental Engineering*, *10*, 100880. https://doi.org/10.1016/j.cscee.2024.100880

Goel, A., Panitz, F., Moghaddam, E. M., Ströhle, J., Epple, B., He, C., & Konttinen, J. (2026). Comparative performance evaluation of biomass chemical looping against conventional gasification technologies. *Energy Conversion and Management: X*, 101828. https://doi.org/10.1016/j.ecmx.2026.101828

Hantoko, D., Adnan, M. A., Dwijayanto, A., Putra, A. F. P., & Hossain, M. M. (2025). Chemical looping gasification of palm oil mill effluent for hydrogen production – An Aspen Plus modeling. *Biomass and Bioenergy, 203*, 108258. https://doi.org/10.1016/j.biombioe.2025.108258

Hoo, K. K., & Said, M. S. M. (2021). Air gasification of empty fruit bunch: An Aspen Plus model. *Bioresource Technology Reports, 16*, 100848. https://doi.org/10.1016/j.biteb.2021.100848

Ilhami, A., Hidayat, T., & Riandi, R. Analisis Trends Produksi dan Potensi Limbah Padat Kelapa Sawit Pada Perkebunan Rakyat di Provinsi Riau. *EL-JUGHRAFIYAH*, *4*(1), 14-22. https://ejournal.uin-suska.ac.id/index.php/jughrafia/article/view/30039

Institute for Essential Services Reform. (2022). *Indonesia Energy Transition Outlook (IETO) 2023*. https://iesr.or.id/en/pustaka/indonesia-energy-transition-outlook-ieto-2023/

IEA. (2023). *Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach*. International Energy Agency Publications. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach

International Energy Agency (IEA). (2024). *Global Hydrogen Review 2024: Advancing Hydrogen for Decarbonization*. Paris: IEA Publications. https://www.iea.org/reports/global-hydrogen-review-2024

IRENA. (2023). *Green Hydrogen Cost Reduction: Scaling up Electrolyzers to Meet the 1.5°C Climate Goal*. International Renewable Energy Agency. https://studylib.net/doc/27498941/irena-green-hydrogen-cost-2020

IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/

Ishaq, H., & Dincer, I. (2020). Comparative assessment of renewable energy-based hydrogen production methods. *Renewable and Sustainable Energy Reviews, 135*, 110192. https://doi.org/10.1016/j.rser.2020.110192

Jiang, L., Hu, S., Syed-Hassan, S. S. A., Wang, Y., & Xu, K. (2023). Steam gasification of biomass for hydrogen-rich gas: A critical review of process parameters, catalysts and mechanisms. *Renewable and Sustainable Energy Reviews, 181*, 113329. https://doi.org/10.1016/j.rser.2023.113329

Kansongue, N., Njuguna, J., & Vertigans, S. (2023). A PESTEL and SWOT impact analysis on renewable energy development in Togo. *Frontiers in Sustainability, 3*, 990173. https://doi.org/10.3389/frsus.2022.990173

Ministry of Energy and Mineral Resources. (2025). *Peta Jalan (Roadmap) Hidrogen dan Amonia Nasional.* Kementerian Energi dan Sumber Daya Mineral. https://ebtke.esdm.go.id/elibrary/peta-jalan-hidrogen-dan-amonia-nasional

Kong, Z. Y., Ang, T. J. N., Ong, H. C., Shi, T., Yeo, C. I., & Yang, A. (2025). Green hydrogen production from oil palm wastes: A techno-economic and environmental perspective. *Energy Conversion and Management, 341*, 120026. https://doi.org/10.1016/j.enconman.2025.120026

Lin, Y., Wang, H., Huang, Z., Liu, M., Wei, G., Zhao, Z., Li, H., & Fang, Y. (2020). Chemical looping gasification coupled with steam reforming of biomass using $NiFe_2O_4$: Kinetic analysis of DAEM-TI, thermodynamic simulation of OC redox, and a loop test. *Chemical Engineering Journal, 395*, 125046. https://doi.org/10.1016/j.cej.2020.125046

Qi, J., Li, H., Chen, G., Yan, B., & Yao, J. (2024). Thermodynamic modeling and performance analysis of chemical looping gasification combined with steam reforming for municipal solid waste: An Aspen Plus approach. *Energy Conversion and Management, 314*, 118655. https://doi.org/10.1016/j.enconman.2024.118655

Qi, J., Liu, J., Chen, G., Yao, J., Yan, B., Yi, W., Zao, H., & Xu, S. (2025). Hydrogen production from municipal solid waste via chemical looping gasification using CuFe2O4 spinel as oxygen carrier: An Aspen Plus modeling. *Energy Conversion and Management, 294*, 117562. https://doi.org/10.1016/j.enconman.2023.117562

Shanmugasundaram, S., Thangaraja, J., Rajkumar, S., Ashok, S. D., Sivaramakrishna, A., & Shamim, T. (2025). A review on green hydrogen production pathways and optimization techniques*. Process Safety and Environmental Protection, 197*, 107070. https://doi.org/10.1016/j.psep.2025.107070

She, J., & Chen, X. (2025). The development and prospect of bio-Mg alloy materials. *Journal of Magnesium and Alloys*, *13*(4), 1383-1385. https://doi.org/10.1016/j.jma.2025.04.005

Tavakoli, N., Pourfayaz, F., & Mehrpooya, M. (2025). Tri-optimization of cost, power and efficiency of a waste biomass gasification integrated with a molten carbonate fuel cell by a combined approach. *Energy, 314*, 134319. https://doi.org/10.1016/j.energy.2024.134319

Waluyo, D., & Rauf, T. (2024). *Limbah Kelapa Sawit untuk Ekonomi Berkelanjutan*. Indonesia.go.id. Retrieved from https://indonesia.go.id/kategori/editorial/8694/limbah-kelapa-sawit-untuk-ekonomi-berkelanjutan?lang=1

Wang, M., Chen, L., Chen, D., Ding, K., Li, B., Lv, P., Song, X., Jiao, Y., Guo, Q, Yu, G., Huang, A., & Wei, J. (2026). Modeling study on biomass gasification for H_2-rich syngas production based on machine learning: A comprehensive review. *Renewable and Sustainable Energy Reviews, 226*, 116223. https://doi.org/10.1016/j.rser.2025.116223

Wei, G., Yao, Y., Cao, J., Yao, W., Wu, X., Yang, X., Yuang, H., Wang, L., Song, Y., & Xie, J. (2025). Kinetics and experimental evaluation of hydrogen-rich synthesis gas from alkali lignin by chemical looping gasification with $NiFe_2O_4$ oxygen carrier. *Renewable Energy, 243*, 122557. https://doi.org/10.1016/j.renene.2025.122557

Wu, Z., Zhu, P., Yao, J., Zhang, S., Ren, J., Yang, F., & Zhang, Z. (2020). Combined biomass gasification, SOFC, IC engine, and waste heat recovery system for power and heat generation: Energy, exergy, exergoeconomic, environmental (4E) evaluations. *Applied Energy*, *279*, 115794. https://doi.org/10.1016/j.apenergy.2020.115794

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