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Influence of Electrolyte Chemistry and Electrode Material on Hydrogen Production Performance in Alkaline Water Electrolysis

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Abstract

Alkaline water electrolysis is a mature and cost-effective technology for hydrogen production; however, the combined influence of electrolyte concentration, electrolyte type, and electrode material under controlled laboratory conditions requires further systematic evaluation. This study experimentally investigates the coupled effects of electrolyte type (NaOH and KOH), concentration (20–30%), and electrode configuration (stainless steel–stainless steel, nickel–stainless steel, and nickel–nickel) on hydrogen production rate and cell energy efficiency using a laboratory-scale alkaline electrolyzer operated at constant electrical conditions (5 V, 1.5 A). The results demonstrate that increasing alkaline concentration enhances hydrogen production and cell efficiency due to improved ionic conductivity and reduced internal resistance. Stainless steel electrodes exhibited the lowest hydrogen production rate (0.047 mL/s), while pure nickel electrodes achieved the highest rate (0.061 mL/s) and maximum efficiency of 44.17%, confirming the superior catalytic activity of nickel toward the hydrogen evolution reaction. The nickel–stainless steel configuration showed comparable performance (0.060 mL/s; 43.36%), indicating that incorporating nickel active sites significantly improves electrochemical performance while potentially reducing material cost. Comparative analysis between NaOH and KOH revealed similar trends, with both electrolytes converging to nearly identical hydrogen production rates (~0.0616 mL/s) and efficiencies (~44.4%) at 30% concentration, suggesting that at sufficiently high concentrations, performance becomes increasingly governed by electrode kinetics rather than electrolyte type. These findings emphasize the critical role of electrode material and electrolyte concentration in optimizing alkaline electrolysis performance and provide practical insights for improving laboratory-scale hydrogen production systems.

Keywords: Alkaline water electrolysis; Hydrogen production; Electrolyte concentration; Sodium hydroxide (NaOH); Potassium hydroxide (KOH).

Introduction

The global climate crisis has underscored the need for a transition to low-emission and sustainable energy systems. Ongoing reliance on fossil fuels not only hastens the exhaustion of natural resources but also substantially contributes to greenhouse gas emissions and environmental deterioration [1]. In addressing these difficulties, international initiatives are progressively concentrating on alternative clean energy solutions, such as natural gas, biofuels, and hydrogen. Among these alternatives, hydrogen has emerged as a promising energy carrier owing to its adaptability and capability to combine various renewable energy sources. Thus, the advancement of green hydrogen (GH_2) production technologies has emerged as a critical need for attaining decarbonization objectives and promoting sustainable energy systems [2].

The global energy transition is accelerating at an unprecedented pace, driven by mounting concerns over climate change and the imperative to decarbonize the global economy. Global installed renewable energy capacity grew by approximately 50% in 2024, reaching around 4,448.1 GW by the end of the year. Solar photovoltaic systems alone accounted for approximately 2,200 GW of this total, reflecting the rapid cost reductions and widespread adoption of solar technology worldwide. Alongside this expansion in generation capacity, the hydrogen economy is also gaining momentum: global installed electrolyzer capacity was projected to reach approximately 5 GW, while total global hydrogen demand remained near 100 Mt, still dominated by fossil fuel-based production methods. This gap between the scale of renewable energy deployment and the current capacity for green hydrogen production underscores the critical need to develop efficient, low-cost water electrolysis technologies.

In this context, green hydrogen energy storage provides a sustainable and efficient solution by serving as a clean and versatile energy carrier. Hydrogen represents a promising alternative fuel due to its abundance and adaptability across multiple sectors. Green hydrogen specifically refers to hydrogen produced through water electrolysis powered by renewable energy sources such as solar, wind, or hydropower. During electrolysis, water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) by applying direct electric current in an electrolyzer. When the electricity supply is entirely derived from renewable sources, the process results in zero greenhouse gas emissions, making it one of the most environmentally sustainable hydrogen production pathways[3, 4].

Electrolysis is widely recognized as the hydrogen production method with the lowest environmental impact. The efficiency of the process can be enhanced by adding electrolytes such as sodium hydroxide (NaOH), which improves the electrical conductivity of the solution and increases the hydrogen production rate [5, 6]. Owing to its high energy efficiency and clean combustion characteristics, with water vapor as the primary byproduct, green hydrogen is considered a key enabler in the transition toward sustainable energy systems. It can function as a fuel, an energy carrier, and an industrial feedstock in transportation, power generation, and various industrial applications, while strongly supporting global decarbonization objectives.

Susilo et al. [7] investigated the effects of electrode material, electric current, and NaOH concentration on HHO gas production using water electrolysis. The maximum flow rate reached 8.08×10^{-4} m^3/s with stainless-steel electrodes at 50 A and 50% NaOH. Based on the electrolysis stoichiometry, the corresponding hydrogen production rate was approximately 5.38×10^{-4} m^3/s. The study confirmed a direct relationship between current, electrolyte concentration, and hydrogen generation performance.

El-Ghetany et al.[2] developed a mathematical model for alkaline water electrolysis using EES software to evaluate the influence of operating and design parameters on hydrogen production performance. The results indicated that a 30 wt% KOH solution provides optimal performance due to its higher conductivity compared to NaOH. Increasing temperature reduced cell voltage (from 1.851 V at 40 °C to 1.677 V at 80 °C), while higher pressure increased the reversible voltage and overall cell voltage. The study also showed that hydrogen production rate improves with larger electrode surface area, higher current density, and increased number of cells, with IrO_2-coated electrodes providing the lowest cell voltage despite cost limitations.

Ramzy and El-Askary [8] experimentally investigated the coupled effects of electrolyte type (NaOH, KOH), concentration (5–20%), and electrode plate number (4–8) on alkaline water electrolysis performance. The results showed that increasing electrolyte concentration to 20% significantly enhanced hydrogen production, with KOH exhibiting slightly superior performance due to higher ionic conductivity. The number of electrode plates had a non-linear impact, with a 6-plate configuration identified as the practical optimum before diminishing returns occurred. The study highlighted the importance of integrated optimization between electrolyte chemistry and electrolyzer design to achieve higher efficiency, thermal stability, and cost-effective hydrogen production.

Saleh and May [9] experimentally investigated hydrogen production via water electrolysis using NaOH and KOH electrolytes under varying voltage, current, time, and concentration conditions. The results showed that KOH outperformed NaOH due to its higher ionic activity, achieving a maximum hydrogen yield of 140 ml at 3 min, 4 A, 10 V, and 5 g/L concentration. The highest Faradaic efficiency recorded was 0.179% for KOH at 5 g/L, compared to 0.130% for NaOH under similar conditions. The study confirmed that hydrogen production increases with time, current, and optimal electrolyte concentration, highlighting the superiority of KOH for enhanced electrolysis performance.

Despite these insights, most previous studies have focused on isolated parameter optimization rather than a systematic evaluation under consistent experimental conditions. In the present work, a structured approach was adopted: first, the effect of NaOH concentration on hydrogen production rate and efficiency was evaluated using stainless-steel electrodes; second, electrode material influence was examined through three configurations—stainless-steel/stainless-steel, nickel/stainless-steel, and nickel/nickel; finally, a comparative analysis of NaOH and KOH electrolytes was conducted using nickel electrodes. This approach provides a comprehensive understanding of the combined effects of electrolyte type, concentration, and electrode material on hydrogen production efficiency.

The novelty of this work lies in the integrated, systematic experimental dataset generated under controlled and identical operating conditions across all variable combinations—an approach that enables direct, unambiguous comparison of the relative contributions of electrode material and electrolyte chemistry. Specifically, this study provides: (i) a quantified performance map for three electrode configurations (SS/SS, Ni/SS, Ni/Ni) using a consistent electrolyte baseline; (ii) a direct efficiency comparison between NaOH and KOH across eight concentration levels using identical nickel electrodes; and (iii) a validated experimental framework applicable for low-cost alkaline electrolyzer prototyping in resource-limited laboratory environments. These contributions are particularly relevant for research groups in developing countries seeking practical benchmarks for hydrogen production using accessible materials.

Methodology

This study employed an experimental methodology to investigate the effects of electrolyte type (NaOH and KOH), concentration, and electrode material on hydrogen production in alkaline water electrolysis. Eight concentrations of each electrolyte (20, 21, 22, 24, 25, 26, 28, and 30 %) were tested to examine trends in conductivity and hydrogen generation efficiency. A single electrolyzer prototype was constructed using PVC tubing, including insulation, sealing, a gas separator, and a DC power supply. The electrolyzer was operated under a compliance-limited mode: a fixed voltage setpoint of 5 V was applied, with the power supply current limited to a maximum of 1.5 A. Under these conditions the cell drew a near-constant current of approximately 1.5 A across all runs, with minor variation (≤ 0.05 A) observed between different electrolyte conditions; cell voltage and current were monitored continuously using a calibrated digital multimeter throughout each experiment. Hydrogen was collected using a gas collection system while recording electrolyte temperature to monitor thermal behavior. Experiments were conducted with different electrode configurations—stainless-steel/stainless-steel, nickel/stainless-steel, and nickel/nickel—to evaluate the effect of electrode material. Finally, a comparative analysis between NaOH and KOH electrolytes was performed to assess differences in hydrogen production performance.

Experimental setup

This study involved the design, construction, and experimental testing of a single laboratory-scale alkaline water electrolyzer shown in Figure 1 using either a plastic electrolysis cell or a 720 mL glass beaker at the Faculty of Engineering. The electrolyzer was powered by a 20 V, 2 A DC power supply, and a laboratory hot plate was used to control the electrolyte temperature. Three electrode configurations were investigated: two stainless-steel electrodes, one stainless-steel and one nickel electrode, and two nickel electrodes, each with a surface area of 0.004822 m². Dilute NaOH and KOH solutions were used as electrolytes.

Hydrogen gas was collected in a gas bag, while a clamp meter monitored the current and K-type thermocouples measured electrolyte temperature throughout the experiments. This setup allowed for a systematic evaluation of the effects of electrolyte type and electrode material on hydrogen production performance. The gas bag collection method was used to measure the accumulated hydrogen volume over a fixed time interval, from which the volumetric flow rate was calculated. The cell anode and cathode gas outlets were separated by the PVC cell body, with hydrogen collected from the cathode side only. Gas volume was recorded at ambient conditions (approximately 1 atm, 22–25 °C); no corrections for water vapor partial pressure or ambient pressure fluctuations were applied, and the reported flow rates should therefore be interpreted as "wet gas at ambient conditions" rather than at standard conditions (STP: 0 °C, 1 atm). This introduces an estimated systematic offset of approximately 3–5% in the absolute volumetric rate, but does not affect the relative trends between experimental conditions, which are the basis for all comparative conclusions in this study. Gas purity was not independently verified; cross-contamination from oxygen is considered negligible given the physical separation of the two electrode compartments within the cell body, but this assumption represents an acknowledged limitation of the current setup. Key experimental parameters are summarized in Table 1 to support reproducibility. The electrode plates had nominal dimensions of approximately 100 mm × 48.22 mm with a measured immersed surface area of 0.004822 m^2 per plate. The stainless-steel electrodes were grade 304, and the nickel electrodes were commercial-purity (99%) flat plates. Electrode surfaces were cleaned with ethanol and rinsed with distilled water prior to each experiment; no additional mechanical or chemical surface treatment was applied. The inter-electrode gap was approximately 10 mm in all configurations. The electrolyte volume was 600 mL (glass beaker configuration). No diaphragm or membrane separator was used between the electrode compartments; gas separation relied on the physical cell geometry and the upward buoyancy of the evolved gas bubbles directed to separate collection points. Readers wishing to replicate this work are encouraged to note that the absence of a membrane separator means some degree of gas crossover cannot be entirely excluded, and is acknowledged as a limitation of this configuration.

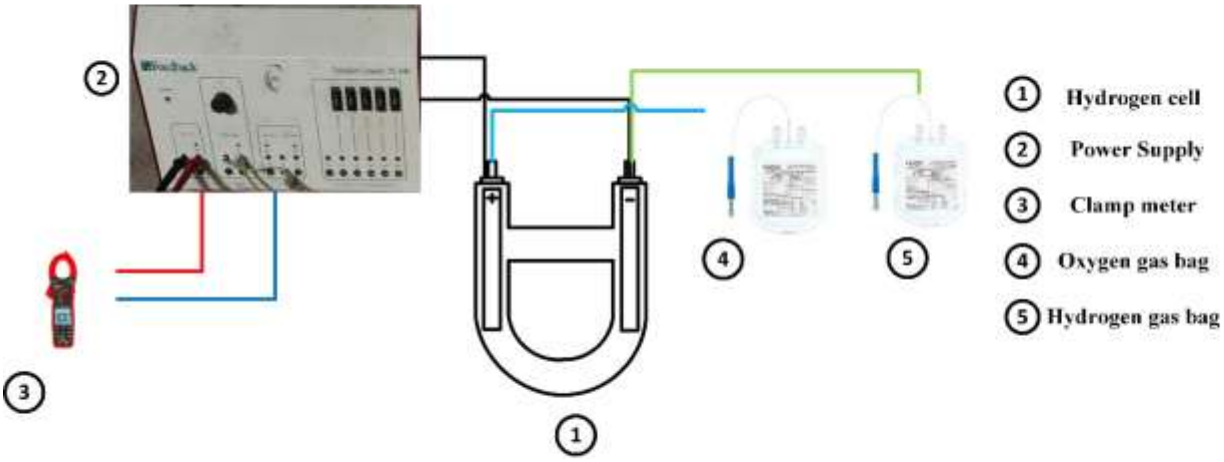


Figure 1. Schematic diagram containing a generation system for hydrogen production

Experimental Procedure

The experimental procedure for evaluating hydrogen production efficiency was conducted as follows:

Effect of electrolyte concentration

The initial experimental configuration incorporated stainless steel electrodes. This preliminary investigation was designed to systematically evaluate the influence of electrolyte concentration on the overall system performance. An aqueous sodium hydroxide (NaOH) solution was employed as the electrolyte. A series of experiments was conducted at concentration levels of 20%, 21%, 22%, 24%, 25%, 26%, 28%, and 30% to quantitatively assess their effect on the electrochemical response and hydrogen generation efficiency.

The system was operated under a controlled power supply set at 5 V with a maximum current of 1.5 A, the experimental setup Is shown in Figure 2.

The operating conditions of 5 V and 1.5 A were selected based on the rated capacity of the available DC power supply and on preliminary trials that confirmed stable, continuous gas evolution across the full range of electrolyte concentrations tested. The theoretical minimum decomposition voltage for water is approximately 1.23 V; in practice, accounting for activation overpotentials and ohmic losses in a simple single-cell laboratory configuration, an applied voltage of 5 V is typical for this class of experiment and is consistent with conditions used in comparable studies [8, 9]. The 1.5 A current limit was imposed to prevent excessive heating and to ensure safe operation of the gas collection system. Future work will investigate a broader range of voltages and current densities to map the full polarization behavior of the cell.

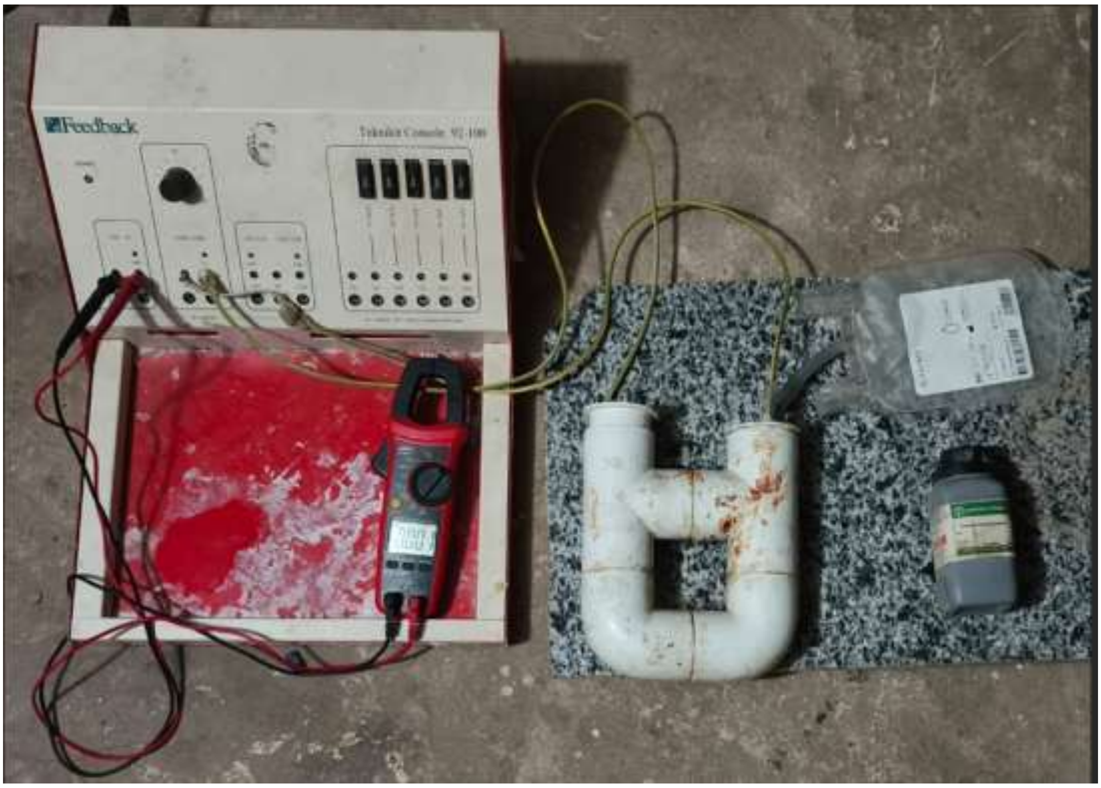


Figure 2. Photograph of the experimental model for electrolyzer

Effect of electrode material

In this section, the influence of electrode material on hydrogen production was investigated. Three electrode configurations were examined under identical experimental conditions. The first configuration employed a pair of stainless-steel electrodes. The second consisted of a stainless-steel cathode paired with a nickel anode. The third configuration utilized two nickel electrodes. All experiments were carried out at a constant applied current to ensure comparability of results.

Effect of Electrolyte Composition

The influence of electrolyte type on hydrogen production was investigated by comparing aqueous solutions of potassium hydroxide (KOH) and sodium hydroxide (NaOH) at various concentrations Figure 3. Maintaining a consistent and high-purity electrolyte is essential to ensure the reproducibility of the experiments, as any degradation or compositional drift can significantly affect the ionic conductivity and electrochemical performance. To mitigate these issues, a strict protocol was followed for electrolyte preparation and handling. Fresh solutions were prepared for each experimental trial using distilled water and analytical-grade pellets. All experiments were conducted under identical operating conditions, including applied current and electrode configuration, to isolate the effect of the electrolyte type on hydrogen generation efficiency.

Figure 3. Electrolysis Media for Potassium Hydroxide (KOH) and Sodium Hydroxide (NaOH) Solutions

Cell Efficiency Calculation

The performance of the electrolysis cell was evaluated in terms of energy efficiency, defined as the ratio between the chemical energy rate of the produced hydrogen and the electrical power supplied to the cell. In this study, the term "cell energy efficiency" (or "electrolyzer efficiency") refers specifically to this electrical-to-chemical energy conversion ratio as defined in Eq. (1). This is distinct from "Faradaic efficiency" (also called current efficiency), which quantifies the fraction of charge that results in hydrogen production versus parasitic reactions. Faradaic efficiency was not measured in this study and is therefore not reported or implied. The cell efficiency was calculated using the following expression:

$$\eta_{cell} = \frac{\dot{m}_{H_2} \times HHV}{V_c \times I} \qquad (1)$$

Where η_{cell} is the cell efficiency, $\dot{m}_{H_2}$is the hydrogen mass flow rate (kg/s), HHV is the higher heating value of hydrogen (J/kg), $V_c$is the cell voltage (V), and I is the applied current (A). The term $V_c \times I$ represents the electrical power input to the electrolysis cell, while $\dot{m}_{H_2} \times HHV$ represents the rate of chemical energy stored in the produced hydrogen. It should be noted that this formulation uses the Higher Heating Value (HHV) of hydrogen (141.8 MJ/kg), which includes the latent heat of condensation of the product water. In practical electrolysis systems operating at low temperature, the Lower Heating Value (LHV = 119.9 MJ/kg) is sometimes preferred since the water vapor is not condensed. The use of HHV in Eq. (1) therefore represents an upper-bound efficiency estimate. This definition is consistent with the approach adopted in alkaline water electrolysis performance studies [2, 11].

Uncertainty

An uncertainty analysis was conducted to assess the precision and reliability of the experimental measurements. Temperature was measured using a K-type thermocouple with an accuracy of ±0.1%. Mass measurements were obtained using a digital balance with an uncertainty of ±0.01%. The volumetric measurements were carried out using a graduated cylinder/beaker with an accuracy of ±0.12%. Electrical parameters, including current and voltage, were recorded using a calibrated digital multimeter with an uncertainty of ±0.5%. These measurement uncertainties were considered in the evaluation of the experimental results and performance calculations. The combined uncertainty in a derived quantity R that depends on independent measured variables $x_1, x_2, ..., x_n$ was calculated using the Kline–McClintock method:

$$\delta R = \sqrt{[(\partial R/\partial x_1 \cdot \delta x_1)^2 + (\partial R/\partial x_2 \cdot \delta x_2)^2 + ... + (\partial R/\partial x_n \cdot \delta x_n)^2]} \quad (2)$$

where δR is the combined uncertainty in the result, $\partial R/\partial x_i$ is the partial derivative of R with respect to each measured variable, and δx_i is the absolute uncertainty of that variable. Applying this to the cell efficiency η_1, which depends on the measured hydrogen volume flow rate (Q), cell voltage (V_1), and current (I), the combined efficiency uncertainty was estimated at approximately ±0.54%, confirming that the reported efficiency values are reliable within the stated measurement precision.

Result and discussion

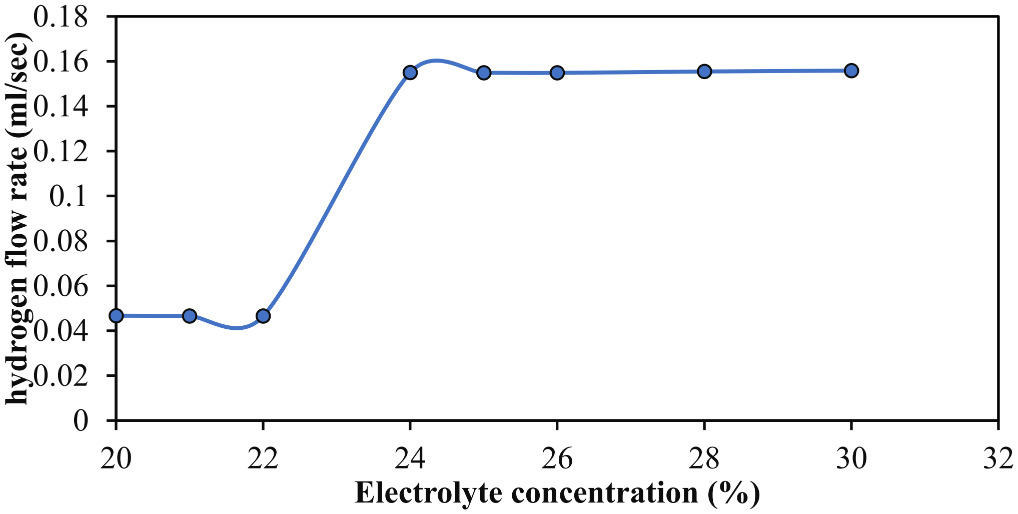
This section presents and discusses the experimental results obtained from the electrolysis tests conducted under varying operating conditions, including electrolyte type (NaOH and KOH), electrolyte concentration (20–30%), and electrode material configuration (stainless steel, nickel, and combined stainless steel–nickel). The analysis focuses on the hydrogen production rate, electrolysis cell energy efficiency, and the influence of these parameters on the overall electrochemical performance of the system. All experiments were conducted at near-ambient electrolyte temperature. The electrolyte temperature was monitored throughout using K-type thermocouples and remained in the range of approximately 22–35 °C across all runs, rising gradually with electrolysis time due to Joule heating. Since no active cooling was applied, temperature was not independently varied and is therefore not presented as a primary result variable. However, the observed temperature range is noted here for transparency, and its potential influence on conductivity and reaction kinetics is acknowledged as a source of inter-run variability. Future work should investigate temperature as a controlled variable over the range of 25–70 °C to fully characterize its effect on hydrogen production performance.

The experimental results in Figure 4a reveal a critical transition in hydrogen evolution kinetics related to NaOH concentration:

The Conductive Surge (20% – 24%): The sharp increase in the hydrogen production rate post-22% is primarily driven by the optimization of ion-pairing and mobility. Recent studies confirm that in alkaline media, increasing the concentration of OH ions minimizes the Ohmic overpotential by providing a denser network for charge transport, which directly scales the current density and gas evolution according to Faraday’s principles [10].

Figure 4b highlights a progressive increase in cell efficiency η_{cell} as the concentration approaches 30%:

Efficiency Enhancement with Concentration: The increase in efficiency with rising NaOH concentration is consistent with a reduction in overall cell losses. While no polarization curves (I–V), Tafel slopes, or EIS measurements were collected in this study to separate ohmic from charge-transfer contributions, the observed trend is in agreement with published literature attributing similar behavior to reduced ohmic resistance at higher ionic concentrations. It is possible that higher NaOH concentrations also facilitate improved adsorption of hydrogen intermediates on the stainless steel surface, effectively contributing to lower activation losses [11]; however, this mechanistic interpretation should be regarded as tentative without supporting electrochemical diagnostics. The primary conclusion that can be drawn here is a clear performance improvement with increasing concentration. Higher NaOH concentrations facilitate better adsorption of hydrogen intermediates on the stainless steel surface, effectively lowering the activation energy of the process [11].



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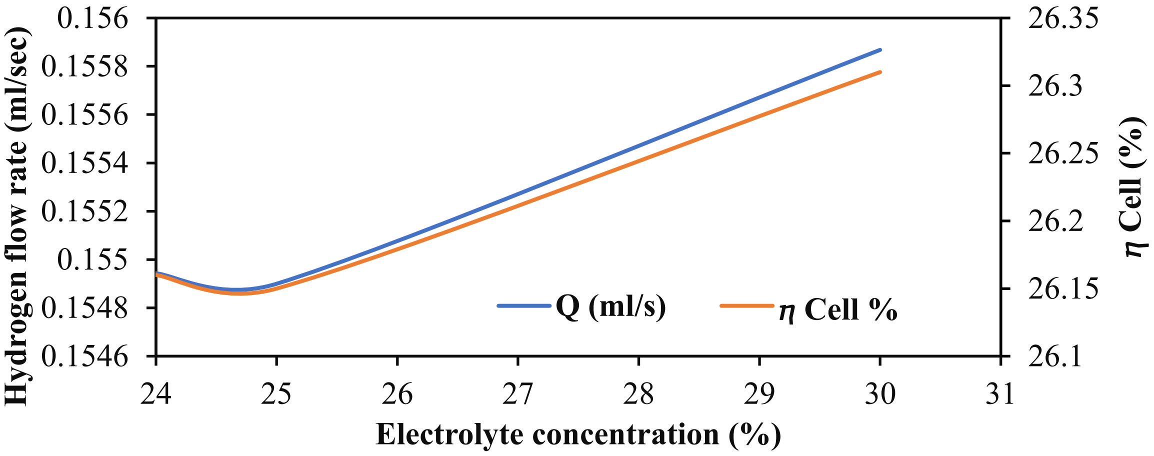


(b)

Figure 4. Effect of Electrolyte Concentration on (a)Hydrogen Production Rate and (b) Cell Efficiency

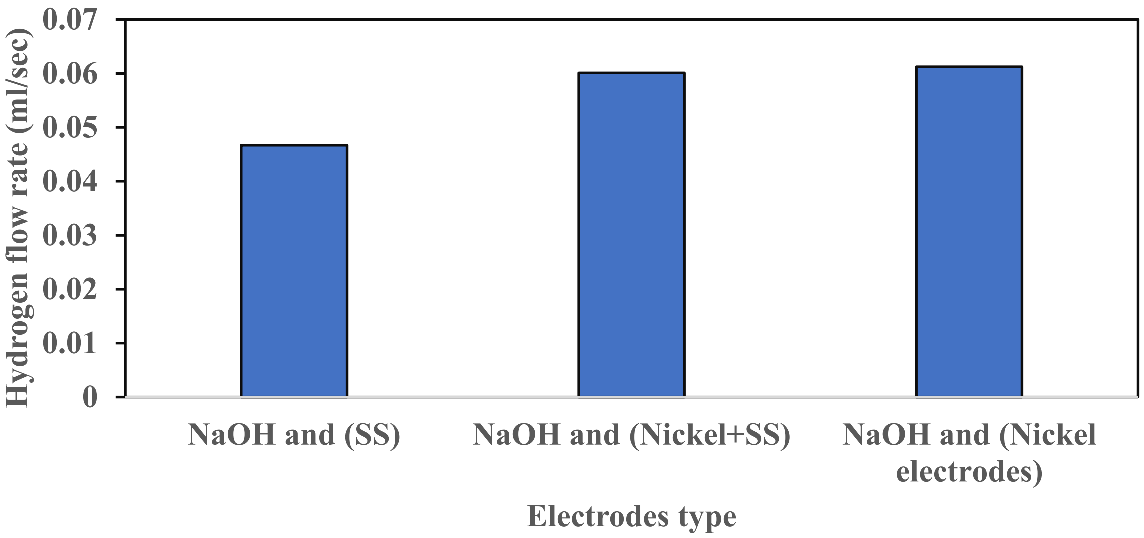
The comparative evaluation of Stainless Steel (SS), Nickel–SS composite, and pure Nickel electrodes reveals a consistent variation in catalytic performance toward hydrogen evolution in alkaline electrolysis. The baseline configuration employing SS electrodes exhibited the lowest hydrogen production rate 0.047 mL/s. Although stainless steel demonstrates adequate chemical stability in alkaline media, its relatively higher activation overpotential limits the electron transfer kinetics of the hydrogen evolution reaction (HER), thereby reducing overall productivity.

In contrast, the use of pure Nickel electrodes significantly enhanced hydrogen generation, achieving a flow rate of 0.061 mL/s. This improvement is consistent with the well-documented superior performance of nickel in alkaline environments, where it is known to exhibit favorable hydrogen adsorption free energy and lower activation losses compared to stainless steel [11]. While no Tafel slope or EIS measurements were performed in this study to directly quantify kinetic parameters, the observed performance difference is in agreement with trends widely reported in the literature and is attributed here to the better electrocatalytic properties of nickel rather than to differences in bulk resistance.

Interestingly, the Nickel–SS composite configuration yielded a comparable hydrogen flow rate of 0.060 mL/s, closely approaching that of pure Nickel. This suggests that incorporating a nickel electrode on one side of the cell provides sufficient catalytic active sites to substantially improve performance relative to the all-stainless-steel baseline, while maintaining structural robustness and potentially reducing material cost. The marginal difference between the Ni/SS and Ni/Ni configurations (≤0.001 mL/s; ≤0.81% efficiency) indicates that the cathode material is the dominant factor governing HER performance in this configuration, which is consistent with the asymmetric role of cathode and anode in alkaline electrolysis. This interpretation is based on observed performance trends; direct mechanistic confirmation would require polarization analysis or impedance spectroscopy.

These trends in hydrogen productivity are further reflected in the calculated energy efficiency of the electrolysis cell. Pure Nickel electrodes achieved the highest efficiency 44.17%, indicating improved conversion of electrical input power into chemical energy stored in hydrogen, with reduced energy losses. The Nickel–SS composite demonstrated a similarly high efficiency of 43.36%, with a marginal difference of less than 1% compared to pure Nickel. The close agreement between these two configurations suggests that the composite electrode offers a technically viable and potentially cost-effective alternative for alkaline hydrogen production systems.

Overall, the results confirm that electrode material plays a critical role in governing both hydrogen generation rate and energy efficiency, primarily through its influence on HER kinetics and electrochemical overpotential. It is important to note that the reported maximum efficiency of approximately 44% is considerably lower than the 60–80% efficiencies commonly cited for advanced commercial alkaline electrolyzers [11]. This discrepancy is expected and can be attributed to several key factors inherent to the laboratory-scale setup used in this study. First, the electrodes used here are planar, unactivated metal plates with relatively smooth surfaces, whereas industrial electrolyzers employ highly porous, activated electrode coatings (e.g., Raney nickel, NiMo alloys) that maximize active surface area and minimize activation overpotential. Second, the cell operated at a fixed low power input (5 V, 1.5 A) without optimization for minimum thermodynamic voltage, meaning a significant portion of the input energy was dissipated as ohmic losses across the electrolyte and contact resistances. Third, industrial systems typically operate at elevated temperatures (60–80 °C) and pressures, which substantially reduce the reversible cell voltage and improve ionic conductivity. Fourth, no membrane or diaphragm separator was used to prevent gas crossover, which introduces additional recombination losses. These design constraints are consistent with a proof-of-concept laboratory investigation and do not undermine the comparative validity of the results; the relative trends observed across electrode materials and electrolyte concentrations remain meaningful and reproducible within the experimental framework.



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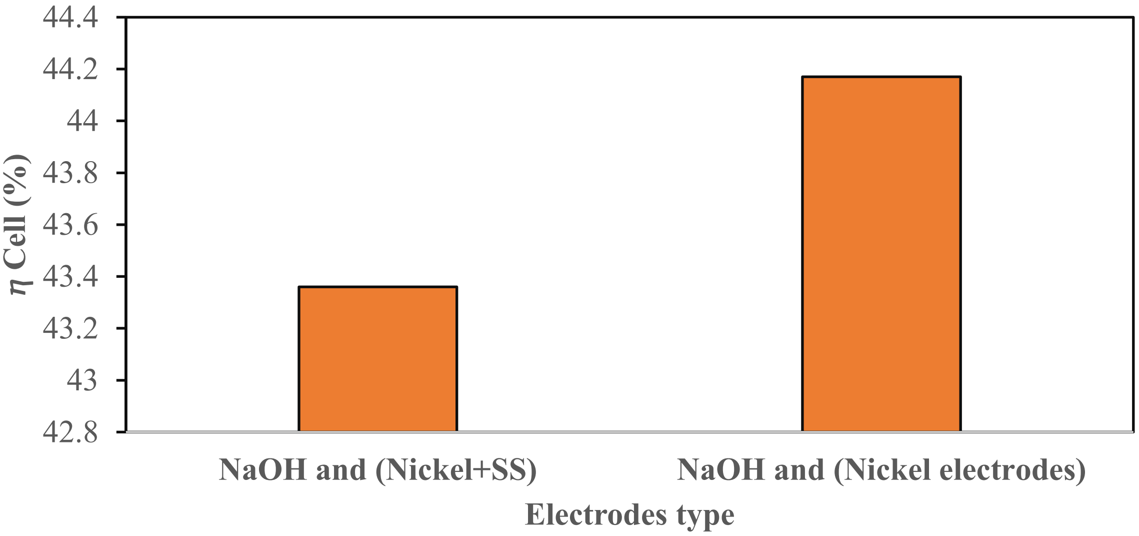


(b)

Figure 5. Impact of Electrode Material on (a)Hydrogen Production Rate and (b) Cell Efficiency

Figure 6(a) illustrates the variation of hydrogen production rate (Q) as a function of electrolyte concentration for both NaOH and KOH using nickel electrodes. The results clearly show that increasing the electrolyte concentration from 20% to 30% enhances hydrogen production for both electrolytes. It should be noted that the NaOH performance values shown in Figure 6 differ from those in Figure 4, despite both using NaOH over the 20–30% concentration range. This apparent discrepancy arises because the two datasets were obtained using different electrode configurations: Figure 4 used stainless-steel/stainless-steel electrodes, while Figure 6 used nickel/nickel electrodes. The superior catalytic activity of nickel accounts for the higher absolute hydrogen production rates and efficiencies observed in Figure 6. The figures are therefore not directly comparable in absolute terms, but both show the same monotonically increasing trend with concentration, which is the primary conclusion drawn from each dataset.

This behavior is primarily attributed to the increase in ionic conductivity with increasing alkaline concentration, which reduces the internal ohmic resistance of the electrolyte and facilitates higher current density at constant applied voltage. Similar trends have been widely reported in alkaline electrolysis systems.

At 20% concentration, NaOH exhibits a slightly higher hydrogen production rate compared to KOH. However, as the concentration increases to 30%, the performance of both electrolytes converges, reaching nearly identical hydrogen production rates (~0.0616 ml/s). This convergence suggests that at higher concentrations, the electrochemical process becomes less sensitive to electrolyte type and more influenced by electrode kinetics and gas evolution dynamics.

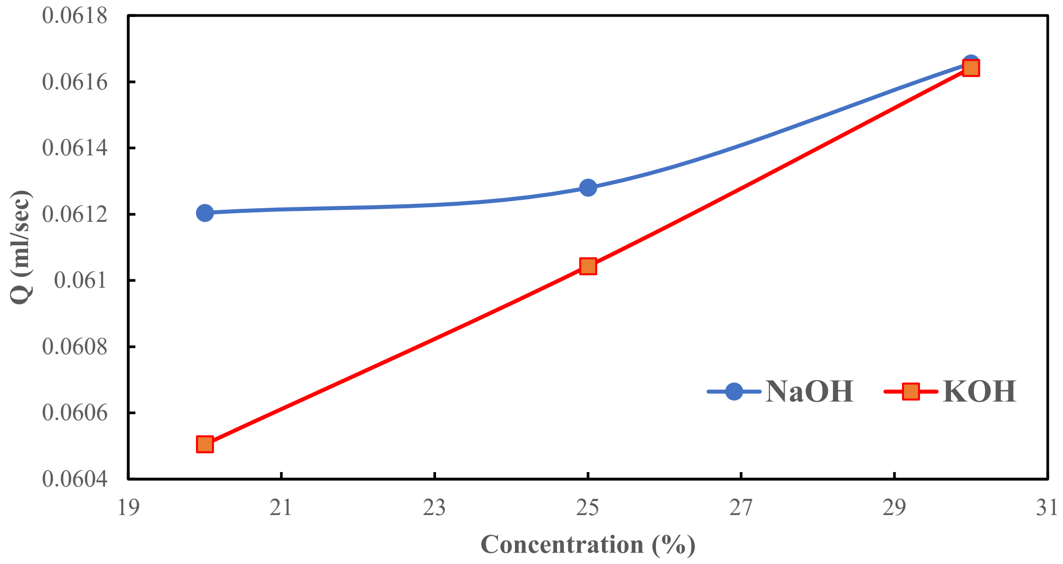
According to Zeng and Zhang [12], once sufficient ionic conductivity is achieved, further performance improvements are increasingly governed by electrode overpotential and mass transport limitations rather than bulk electrolyte resistance. Therefore, the convergence observed at 30% concentration is consistent with established electrochemical theory.

Figure 6(b) presents the variation of cell efficiency with electrolyte concentration. The efficiency increases progressively for both NaOH and KOH as concentration increases.

This improvement is directly related to the reduction in ohmic losses within the electrolyte. As electrolyte conductivity increases, the voltage drop across the solution decreases, leading to better energy utilization and higher overall efficiency. Similar findings have been reported in alkaline water electrolysis studies [12].

At lower concentration (20%), NaOH shows slightly higher efficiency than KOH. However, at 30%, both electrolytes exhibit nearly identical efficiencies (~44.4%). This indicates that at higher concentration levels, the system performance becomes dominated by electrode surface reactions and gas bubble coverage effects rather than differences in electrolyte conductivity.

Ramzy and El-Askary [8] also reported that increasing alkaline electrolyte concentration enhances electrolysis efficiency up to a certain level, beyond which performance differences between NaOH and KOH become less pronounced due to electrochemical and mass transfer constraints



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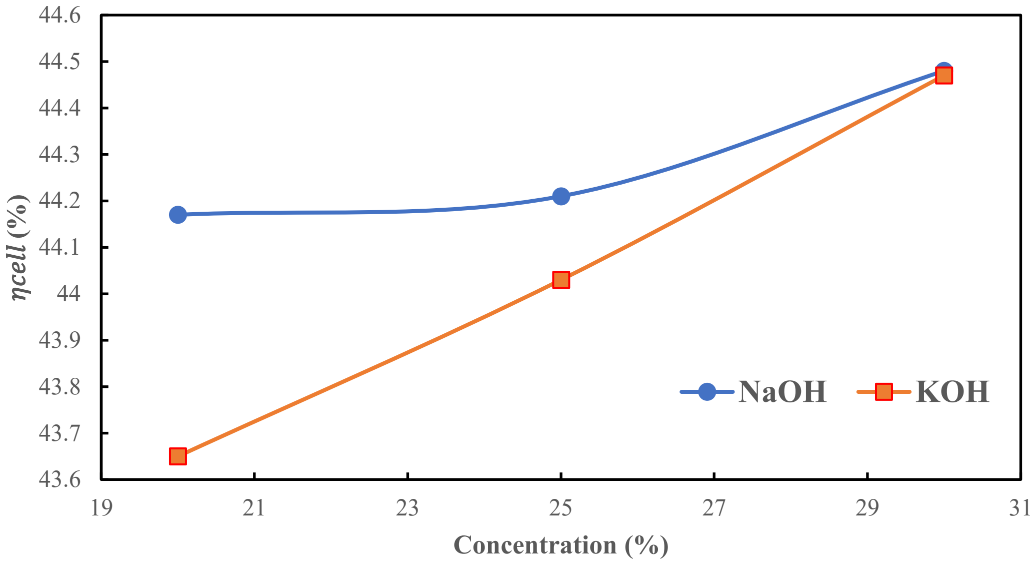

(b)

Figure 6. Comparative Performance Analysis of KOH and NaOH Electrolytes Using Nickel Electrodes (a)Hydrogen Production Rate and (b) Cell Efficiency

Conclusion

This study presented a systematic experimental investigation of the effects of electrolyte concentration, electrode material, and electrolyte type on hydrogen production performance in a laboratory-scale alkaline water electrolyzer operated under constant electrical conditions (5 V, 1.5 A).

The results demonstrated that increasing NaOH concentration from 20% to 30% enhanced both hydrogen production rate and cell efficiency. The improvement is attributed to increased electrolyte conductivity and reduced internal ohmic resistance, which promote higher effective current density and improved electrochemical performance.

Electrode material showed a pronounced influence on hydrogen evolution performance. Stainless steel electrodes yielded the lowest hydrogen production rate 0.047 mL/s due to higher activation overpotential and limited catalytic activity toward the hydrogen evolution reaction (HER). Replacing stainless steel with nickel significantly improved hydrogen generation, reaching 0.061 mL/s with pure nickel electrodes. The nickel–stainless steel configuration achieved a comparable production rate 0.060 mL/s, indicating that incorporating nickel active sites substantially enhances HER kinetics while maintaining structural robustness. These trends were consistently reflected in the calculated cell efficiency, where pure nickel achieved the highest efficiency 44.17%, followed closely by the nickel–stainless steel configuration 43.36%.

A comparative analysis between NaOH and KOH electrolytes using nickel electrodes revealed that both electrolytes exhibit increasing hydrogen production rate and efficiency with increasing concentration. At 20%, NaOH showed slightly higher performance; however, at 30%, both electrolytes converged to nearly identical hydrogen production rates ~0.0616 mL/s) and efficiencies ~44.4%. This convergence suggests that, at sufficiently high concentration, the electrolysis process becomes less sensitive to electrolyte type and increasingly governed by electrode kinetics and gas evolution phenomena rather than bulk ionic conductivity differences.

Overall, the study confirms that hydrogen production performance in alkaline electrolysis is strongly influenced by the combined effects of electrolyte concentration and electrode material. Nickel-based electrodes significantly enhance hydrogen evolution efficiency, while increasing alkaline concentration improves system performance up to the investigated upper limit (30%). The findings provide a coherent experimental basis for optimizing laboratory-scale alkaline electrolyzers under controlled operating conditions.

Future research should extend the concentration range beyond 30% to determine the true optimal operating point and to assess the influence of viscosity and mass transport limitations at higher alkaline concentrations. In addition, investigating a wider range of current densities would allow evaluation of polarization behavior and overpotential contributions under industrially relevant conditions. Furthermore, future experiments should implement a formal replication protocol with a minimum of three repeats per condition ($n \geq 3$) so that mean values and standard deviations can be reported, and error bars included in all performance figures. This would allow statistical assessment of whether observed differences between electrolyte types and electrode configurations are significant rather than within measurement noise — a limitation of the present single-run dataset that is acknowledged here.

Surface modification techniques such as nickel coating thickness optimization, surface roughening, or incorporation of catalytic additives could be explored to further enhance hydrogen evolution kinetics while maintaining cost efficiency.

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