IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 7 (2026) 108-122
https://publisher.uthm.edu.my/ojs/index.php/ijie

Influence of Water Source and Electrolyte pH on Hydrogen Production Efficiency in Laboratory-Scale PEM Electrolysis

Frederick T.T.N[1,2], Jais Lias[2]*, M.K. Ahmad[1,2]*, Shazleen Ahmad Ramli[1,2], M. A. H Hamdan[3], Kim Seng Ng[1,2], M. H. Mamat[4], M. Y. Ahmad[5]

[1] *Microelectronics and Nanotechnology Shamsuddin Research Centre (MiNT-SRC), Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Batu Pahat, Johor, MALAYSIA*
[2] *Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400, MALAYSIA*
[3] *Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA*
[4] *NANO-ElecTronic Centre (NET), School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Selangor, Shah Alam, 40450, MALAYSIA*
[5] *Engineering Division, Nanorian Technologies Sdn. Bhd., A-G-15 & 17, Jalan Goodview 15, Goodview Heights, 43000 Kajang, Selangor, MALAYSIA*

*Corresponding Author: jaisl@uthm.edu.my, akhairul@uthm.edu.my
DOI: https://doi.org/10.30880/ijie.2026.18.07.008

Article Info

Received: 4 June 2026
Accepted: 25 October 2026
Available online: 2 November 2026

Keywords

Hydrogen production, Proton Exchange Membrane (PEM), water electrolysis, electrolyte pH, water source, renewable energy, Hydrogen Evolution Reaction (HER), membrane-based reactor

Abstract

Hydrogen production via water electrolysis represents a scalable and zero-emission pathway for sustainable energy applications. This study evaluates the effects of water source and electrolyte pH on hydrogen generation efficiency using a membrane-based electrolysis system integrating Proton Exchange Membrane (PEM) and Membrane-Based Reactor (MBR) technologies. In the first condition, untreated normal tap water and deionized (DI) water were compared under identical operational parameters. Results indicate that tap water achieved a superior hydrogen production rate of 0.1443 L/min, exceeding the 0.1356 L/min obtained with DI water, attributed to the enhanced ionic conductivity of tap water. In the second condition, the influence of electrolyte pH was examined exclusively using tap water across a pH range of 5 to 10. Peak hydrogen production was recorded at pH 6, corresponding to an optimal balance of proton availability, ionic mobility, and electrode stability, with an output of 0.1443 L/min. Deviations toward strongly acidic (pH 5) or alkaline conditions (pH ≥ 8) resulted in reduced hydrogen evolution rates due to increased overpotentials, elevated system resistance, and gas bubble accumulation. These findings underscore the electrochemical advantages of moderate ionic content in water sources and the critical role of pH regulation in maximizing hydrogen production efficiency for decentralized electrolysis systems.

This is an open access article under the CC BY-NC-SA 4.0 license.

1. Introduction

Hydrogen has become a key energy carrier in the global transition toward low-carbon energy systems. Its high energy density, zero-emission potential, and broad applications in energy storage, power generation, transportation, and industry make it essential for reducing greenhouse gas emissions and supporting decarbonization efforts [1]. Among the various hydrogen production pathways, water electrolysis is particularly attractive due to its environmental friendliness and potential for integration with renewable energy sources such as solar, wind, and hydroelectric power [2] in Figure 1. Water electrolysis is a well-established electrochemical process that converts liquid water (H_2O) into its elemental gases, hydrogen (H_2) and oxygen (O_2), by applying direct current through an electrolysis cell [3]. The overall reaction for water electrolysis was shown in equation 1:

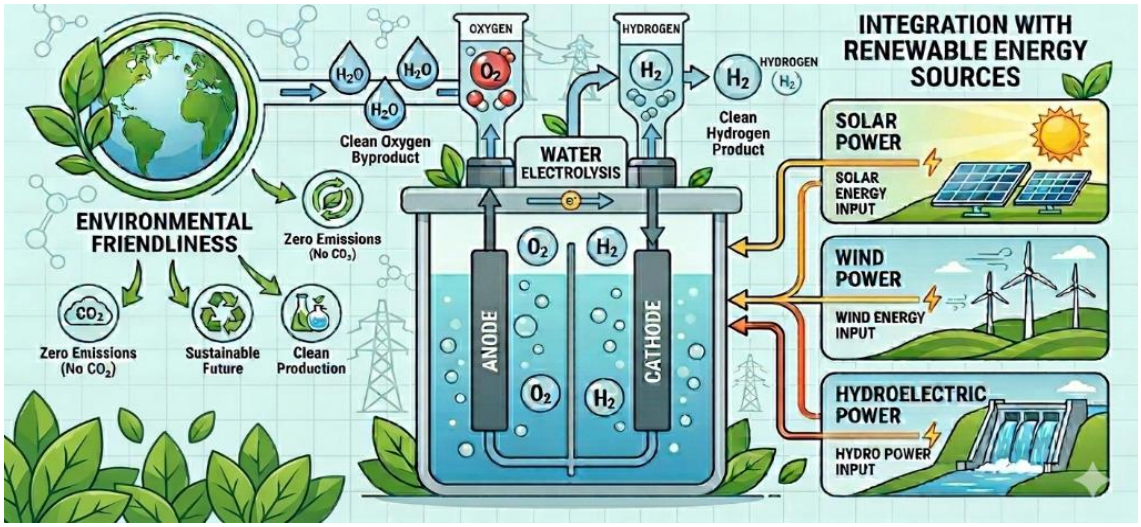


Fig. 1 *Water electrolysis: green pathway to hydrogen production*

$$2H^20\ (1) \rightarrow 2H_2\ (g) + O_2\ (g) \tag{1}$$

This process is facilitated by two simultaneous half-cell reactions occurring simultaneously at each electrode. At the cathode, the Hydrogen Evolution Reaction (HER) takes place. Here, either hydrogen ions (H^+) or water molecules which depending on the electrolyte's pH will accept electrons supplied by the external circuit to form molecular hydrogen gas (H_2) [4]. This reaction is essential to hydrogen production technologies, as it is the primary mechanism for generating hydrogen. In acidic environments where hydrogen ions are plentiful, the HER proceeds via the reduction of protons according to the reaction 2 and reaction 3:

$$2H^+\ (aq) \rightarrow 2e^- \rightarrow H_2(g) \tag{2}$$

$$2H_20\ (1) + \ 2e^- \rightarrow H_2\ (g) + 2OH^-\ (aq) \tag{3}$$

Meanwhile, at the anode, the Oxygen Evolution Reaction (OER) occurs. The fundamental mechanisms of Hydrogen Evolution Reaction (HER) & Oxygen Evolution Reaction (OER) show in Figure 2 below. In this oxidation half-reaction, water molecules are oxidized to release oxygen gas (O_2), with the simultaneous generation of protons (H^+) and electrons [5]. The electrons generated at the anode travel through the external circuit and are delivered to the cathode, closing the electrical loop and sustaining the electrolysis cycle. In acidic conditions, this process is represented by the reaction 4:

Int. Journal of Integrated Engineering Vol. 18 No. 7 (2026) p. 108-122

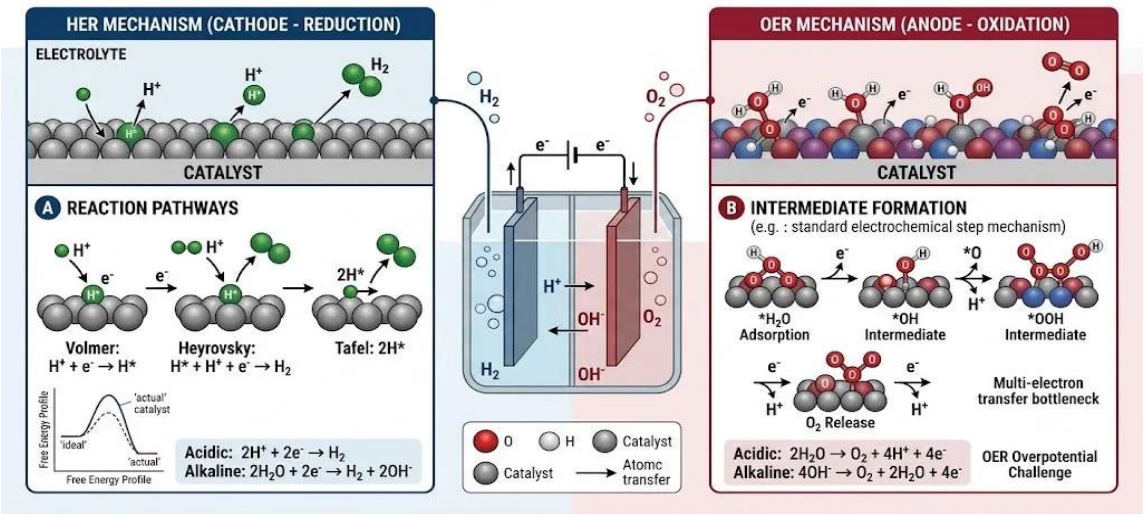


Fig. 2 *Fundamental mechanisms of Hydrogen Evolution Reaction (HER) & Oxygen Evolution Reaction (OER)*

$$2H_20\,(1) \rightarrow\ 2e^{-}H_2\,(g) + 2OH^{-}\,(aq) \tag{4}$$

Unlike prior work focused on alkaline systems with added electrolytes [6], [7], this study explores natural ionic content in tap water without additives under varying pH conditions. Despite advances in system development and optimization, the electrochemical efficiency and long-term viability of water electrolysis technologies continue to be governed by fundamental operational parameters, particularly the physicochemical characteristics of the water and the composition of the electrolyte. Even with complex system designs, these underlying variables often represent performance bottlenecks if not properly managed. Dissolved ions, salts, and organic contaminants present in tap water can increase system resistance, promote electrode fouling, and trigger side reactions that reduce hydrogen yield and efficiency [8]. These impurities, often originating from naturally occurring minerals or anthropogenic pollutants, compromise the conductivity of the electrolyte by introducing competing ionic species and reducing the effective mobility of charge carriers [9]. In addition, surface adsorption of organic molecules or precipitation of insoluble compounds on electrode surfaces can obstruct active catalytic sites, deteriorate electrode performance and increase maintenance requirements [5]. Unintended redox reactions may also occur, diverting energy away from the desired hydrogen evolution pathway and thereby decreasing the system's faradaic efficiency. The electrolyte pH further influences ionic conductivity, electrode stability, and the kinetics of the hydrogen evolution reaction [10] Electrolyte pH dictates the speciation of charge carriers, such as H^+ ions in acidic media and OH^- ions in alkaline media. Thus, it directly affects ion transport rates and electrode reaction mechanisms. It also impacts the thermodynamic and kinetic barriers associated with the hydrogen evolution and oxygen evolution reactions, influencing both the onset potential and reaction rate [11]. Moreover, certain electrode materials exhibit pH-dependent corrosion behavior, which can shorten system lifespan if operated under unsuitable pH conditions. Deviations from the optimal pH range, whether excessively acidic or highly alkaline, can lead to elevated overpotentials, electrode degradation, gas bubble accumulation, and reduced system efficiency [12]. Specifically, non-ideal pH levels increase the energy required to drive the electrochemical reaction will reduce the system's energy efficiency. Furthermore, extreme pH conditions can accelerate the corrosion of metal electrodes or the breakdown of membrane materials, compromising the integrity of the electrolysis cell [13]. Additionally, excessive gas bubble formation on electrode surfaces can physically block active sites, increase local resistance and reduce mass transfer rates, all of which contribute to a decline in overall hydrogen production performance [14]. Table 1 listed the key parameters and the problems used to discuss in this research.

Table 1 *Key parameters and core problems addressed in the electrolysis system*

Key Parameter	Variables	Addressed Problem
Water Source Purity	Tap water vs Deionized water	One of the biggest practical barriers to small-scale, off-grid hydrogen production is the dependence on highly purified water, like deionized (DI) water, which is both costly and difficult to source outside of laboratory settings. Real-world water sources, on the other hand, naturally carry dissolved ions and while these have long been blamed for clogging electrodes, triggering unwanted side reactions, and cutting hydrogen output, they are far more accessible and affordable.
Electrolyte pH	Evaluated range: pH 5 to 10	When electrochemical conditions drift away from their sweet spot, performance takes a serious hit. Highly acidic environments demand more energy to drive the reaction and eat away at electrodes over time, while strongly alkaline conditions raise internal resistance and cause gas bubbles to pile up which physically blocking the very sites where catalysis needs to happen.

These challenges are particularly relevant for decentralized or small-scale hydrogen production systems, which often operate under resource-constrained conditions with minimal infrastructure support. Like the area from rural communities, mobile or off-grid installations, pilot-scale prototypes, and developing regions. The chance of these places having consistent, high-quality input water is frequently limited. Water sources such as municipal supplies, groundwater, or harvested rainwater often vary in ionic composition, organic content, and contamination levels [15].

Therefore, understanding how variations in water source and electrolyte pH influence hydrogen generation is essential for optimizing system performance [16], as these two parameters jointly determine the electrochemical environment in which key reactions like the Hydrogen Evolution Reaction (HER) and Oxygen Evolution Reaction (OER) occur. Differences in water composition can alter conductivity, electrode behavior, and reaction pathways, while pH shifts directly impact ion transport dynamics and catalyst stability [17]. In practical applications where tap water may serve as a more accessible but lower-purity alternative to deionized (DI) water, so evaluating its electrochemical suitability becomes vital. Tap water is often preferred for economic and logistical reasons; however, its non-uniform composition can introduce challenges like scaling, reduced conductivity, or parasitic reactions [9], [18]. Gaining insight into its behavior under varying pH conditions informs realistic system designs that are both cost-effective and robust in real-world deployments.

This study investigates the combined effects of water quality, specifically comparing DI water and tap water, along with varying pH conditions ranging from 5 to 10, on hydrogen production efficiency. In particular, the investigation aims to determine how the purity level of the water source and the electrochemical environment created by different pH values influence the rate and stability of hydrogen evolution during electrolysis. Deionized (DI) water, which is nearly free of dissolved ions, serves as a benchmark for high-purity conditions, whereas tap water represent a more accessible but ion-rich medium which offers insight into practical, real-world scenarios where purification infrastructure is limited or absent. The pH values were chosen to encompass acidic, neutral, and alkaline regimes to capture a comprehensive picture of system behavior across typical electrochemical operating ranges. A laboratory-scale electrolysis system was utilized to assess how these parameters affect hydrogen output under controlled conditions. The system was designed to isolate the influence of water source and pH by maintaining constant temperature, voltage, electrode configuration, and membrane separation, ensuring that any observed variation in hydrogen production rate could be directly attributed to changes in water chemistry and electrolyte pH. This controlled setup enables precise measurement of hydrogen evolution rate, allowing for reproducible and quantifiable performance comparisons across test conditions. The findings provide direct insights into the importance of water purity and pH control for stable, efficient hydrogen production, particularly in applications where resource limitations constrain water treatment options. These results highlight the critical relationship between electrolyte composition and electrochemical efficiency, emphasizing that even modest deviations in water quality or pH can result in significant performance losses due to increased internal resistance, electrode degradation, or impaired reaction kinetics [19]. In resource-constrained environments where advanced purification systems are not feasible, these insights help inform the selection of locally available

Int. Journal of Integrated Engineering Vol. 18 No. 7 (2026) p. 108-122

water sources and guide the implementation of basic conditioning methods, such as pH adjustment or filtration, to improve system reliability. This work contributes to establishing practical operational strategies for improving hydrogen generation efficiency in both centralized and decentralized energy systems. By identifying the specific operating conditions, such as optimal pH levels and acceptable water quality thresholds, that can be used to maximize hydrogen output, this research supports the development of scalable and adaptive electrolysis technologies. These strategies can be applied in industrial-scale plants with rigorous quality controls as well as in off-grid or rural systems with minimal technical infrastructure, thereby broadening the accessibility and sustainability of hydrogen as a clean energy carrier.

2. Experimental Design

2.1 Method Implementation

A laboratory-scale water electrolysis system was established to systematically evaluate the hydrogen production efficiency. The setup included an electrolysis cell powered by a DC supply, integrated with a water reservoir and a gas collection unit for accurate monitoring of hydrogen generation. The schematic diagram of the complete system configuration is shown in Fig. 3, while Fig. 4 provides specifications commercially procured water tank utilized in the experimental setup to ensure consistent experimental conditions.

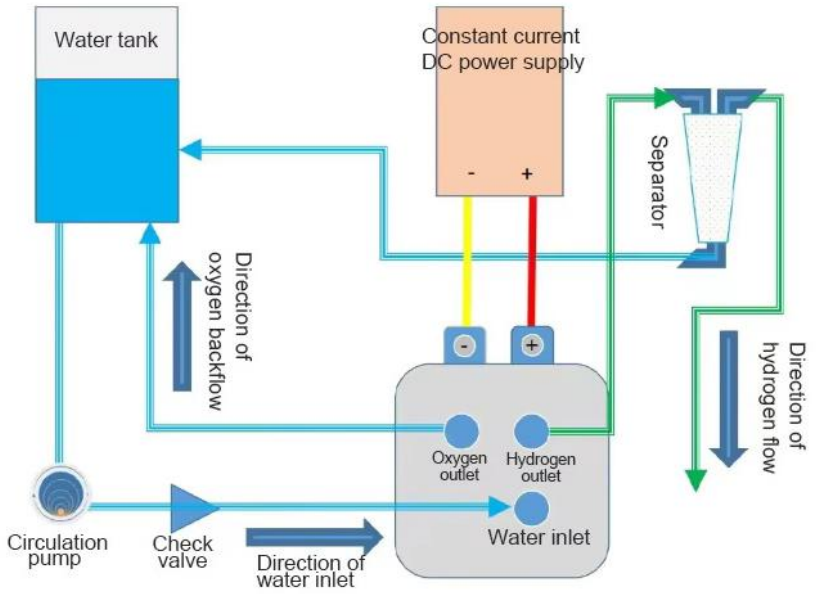
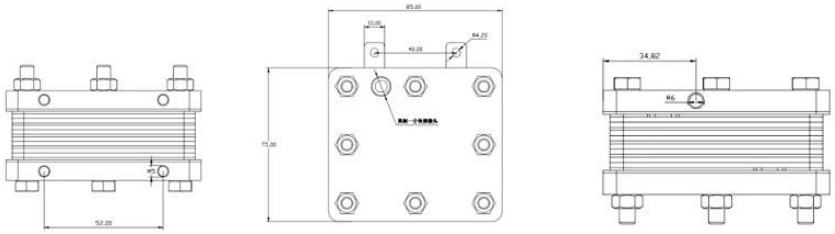


Fig. 3 *Hydrogen production system schematic diagram*



Electrolysis cell specifications range	Recommended water tank size
1000ml-2000ml	≥4L
2000ml-3000ml	≥4.5L

Fig. 4 *Specifications of the commercially procured water tank utilized in the experimental setup*

The specifications of the water tank, detailed in Fig. 4, are critical for maintaining the stability of the electrochemical environment during the experiments. The total volume of the electrolyte reservoir acts as an essential control variable to validate the recorded outcomes. First, a properly sized tank (such as the ≥4L requirement for a 1000–2000 ml cell capacity) provides a sufficient fluid volume to buffer against localized pH fluctuations near the electrodes, ensuring that the bulk electrolyte pH remains stable throughout the duration of the testing. Furthermore, the tank's volumetric scaling provides the necessary thermal mass to dissipate the heat generated during continuous electrolysis. This prevents rapid temperature increases in the recirculating water, which could otherwise alter ionic conductivity and reaction kinetics, thereby skewing the hydrogen production rates. Finally, strictly matching the tank volume to the electrolysis cell capacity ensures continuous, optimal fluid pressure. This prevents the circulation pump from cavitating or starving the Membrane-Based Reactor of water, guaranteeing that the recorded fluctuations in hydrogen production are solely attributable to the controlled variables of water quality and pH value.

This experiment used both Proton Exchange Membrane (PEM) technology and a Membrane-Based Reactor (MBR) to enhance system performance. The PEM selectively facilitates proton transfer from the anode to the cathode while preventing gas crossover, thereby improving hydrogen purity and system efficiency [20]. The MBR integrates an ion-selective membrane between the electrodes, providing enhanced pH control, improved ionic conductivity, and more effective gas separation [21]. Together, the use of PEM and MBR reduces system resistance, stabilizes the electrochemical environment, and contributes to increased hydrogen production rates. Fig. 5 provides schematic diagram of the Membrane-Based Reactor system especially the central grey unit which integrates an ion-selective membrane between the electrodes, providing enhanced pH control, improved ionic conductivity, and more effective gas separation.

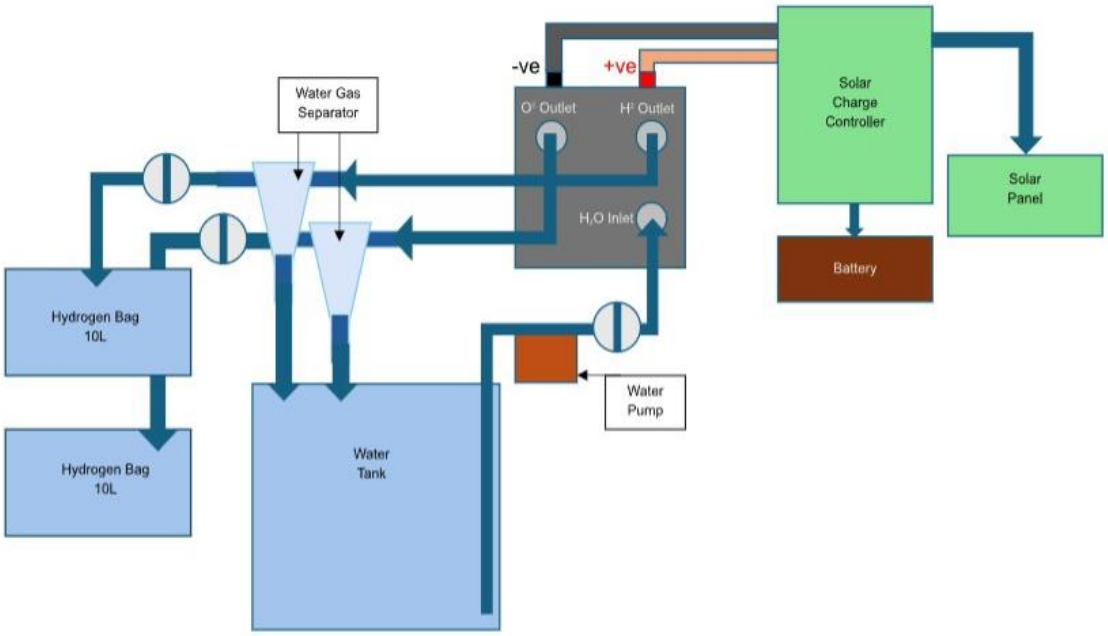


Fig. 5 *Schematic diagram of membrane-based reactor system*

To ensure optimal system operation, specific electrical conditions were maintained throughout the experiment. It is important to note that the minimum voltage requirement for effective PEM operation is 8.0 volts; operation below this threshold results in insufficient proton exchange, rendering the system non-functional. The electrolysis generator employed in this study is capable of a maximum output of 8.5 volts and a peak current of 3.33 amperes, which defines the upper operational limits of the system. These parameters were carefully controlled to prevent system overloading and to maintain stable electrochemical performance. During electrolysis, both hydrogen and oxygen gases are produced through the water-splitting reaction. However, in this study, only hydrogen production was monitored and analyzed, as the primary focus is on optimizing hydrogen output. The generated oxygen was released but not utilized in the subsequent evaluation process.

Two water sources were compared: deionized (DI) water and tap water. The pH of the electrolyte was adjusted across a range of values from pH 5 to pH 10 using acid or base additions. For (pH < 7), acetic acid (CH_3COOH) was used to create the acidic condition for the tap water. Refer to tap water buffering capacity and alkalinity, approximately 100-200ml of household vinegar was required to adjust 10 litres of tap water to pH 5-6. The acid was added in a single dose and stirred thoroughly to ensure homogeneous mixing. pH was monitored

using a pH meter. For alkaline conditions (pH > 7), sodium hydroxide (NaOH) was added to tap water to increase the pH condition from acid/neutral to base conditions. A single-dose addition of NaOH was used. A calculated amount of NaOH solution (e.g., ~0.01–0.05 mol per 10 L, depending on the target pH and buffering strength) was added and stirred uniformly. pH was measured until the desired value (7–10) was achieved. The following chemical equations 5 and 6 showed the dissociation for acideic and alkaline as below:

$$\text{Acidic: } CH_3COOH \rightarrow CH_3COO^- + H^+ \quad (5)$$

$$\text{Alkaline: } NaOH \rightarrow Na^+ + OH^- \quad (6)$$

The impact of electrolyte pH was also investigated by adjusting the water to specific pH levels, covering acidic, neutral, and alkaline environments (pH 5, 6, 7, 8, 9, and 10). Hydrogen production rates were recorded over time, enabling the evaluation of instantaneous output for each water source and pH condition. The experiments aimed to determine how variations in water quality and electrolyte pH affect system efficiency and gas production performance. The system design ensured constant temperature, applied voltage, electrode configuration, and membrane separation during all trials, isolating the influence of water chemistry and electrolyte pH. This controlled setup enabled precise measurement of hydrogen evolution rates, allowing for reproducible performance comparisons across different experimental conditions.

3. Result and Discussion

To further justify the experimental outcomes of this study, the performance of the proposed Membrane-Based Reactor was benchmarked against recent literature focusing on water electrolysis and electrolyte conditions. As summarized in Table 2 which showed the comparison of the present study's findings with recent literature, this study provides the perspective, particularly regarding the water source impact, efficiency optimization in water electrolysis, & the PEM electolyzer operational bottlenecks contrasting with traditional models that strictly rely on highly purified water sources.

Table 2 *Comparison of the present study's findings with recent literature*

Focus	Key Findings	Comparison
Water source impact (DI vs. Tap vs. River water) [22]	Earlier work found that DI water produced more raw hydrogen than tap water, though tap water was recognized as a far more economical option in practice.	Our findings tell a different story. Tap water actually outperformed DI water in hydrogen output — 0.1443 L/min compared to 0.1356 L/min. This supports our hypothesis that the trace minerals naturally present in tap water can reduce internal resistance and, at least in the short term, do not cause meaningful electrode fouling.
Efficiency optimization in water electrolysis [23]	Previous research established that cutting energy losses in electrolysis comes down to fine-tuning the ionic environment to push past the sluggish reaction kinetics of both HER and OER.	Our work takes this further by identifying a precise operating point — pH 6. A mildly acidic environment strikes the best balance between proton availability and low resistance, outperforming both more acidic (pH 5) and more alkaline (pH 9–10) conditions.
PEM Electrolyzer operational bottlenecks [24]	It has also been noted that scaling up PEM electrolysis is largely held back by its strict demand for ultra-pure water, which drives up costs considerably.	Our results reinforce the case that achieving strong performance with ordinary tap water is not only possible but practical — offering a cost-effective route to decentralized hydrogen production without the burden of expensive water purification systems.

3.1 Effect of Water Source on Hydrogen Production

The effect of water source on hydrogen production was studied by comparing deionized (DI) water and tap water under identical conditions. Both water types were tested using the same electrolysis generator, operating within its safe limits of maximum 8.5 volts and 3.33 amperes, ensuring consistent and reliable results. The system voltage was maintained at or above 8.0 volts, the minimum requirement for effective Proton Exchange Membrane (PEM) functionality, to enable efficient proton transfer and hydrogen production. Hydrogen gas was the primary target of the investigation, with oxygen generated as a by-product but not utilized or quantified, consistent with the focus on optimizing hydrogen output.

These two types differ mainly in purity like the DI water contains no dissolved salts or organics, while tap water includes small amounts of minerals and ions from treatment and pipes. Table 3 shows the average hydrogen production rate using tap water, and Table 4 shows the average hydrogen production rate using DI water. These tables allow direct comparison of hydrogen output over time under the same electrolysis conditions. Key settings like current, voltage, and electrode design were kept constant to ensure accurate results. The results show that tap water consistently produced more hydrogen than DI water. Although DI water is typically considered more favourable due to its high purity and low impurity content which can enhance electrochemical stability. However, tap water demonstrated higher hydrogen production rates at most test points under the given experimental conditions. Fig. 6 shows visual comparison with hydrogen production rates over time for both water types. The figure confirms the data in the tables and clearly shows the performance difference between tap and DI water.

Table 3 *Average hydrogen production rate using tap water*

Volume H_2 (L)	Time (min)	Average H_2 Production (L/min)	∑Time (min)	∑Average H_2 Production (L/min)
0.1	0.783	0.1277	0.783	0.1277
0.2	1.350	0.1481	0.567	0.1765
0.3	2.050	0.1463	0.700	0.1429
0.4	2.750	0.1455	0.700	0.1429
0.5	3.550	0.1408	0.800	0.1250
0.6	4.200	0.1429	0.650	0.1538
0.7	4.917	0.1424	0.717	0.1395
Average		0.1443		0.1440

Table 4 *Average hydrogen production rate using DI water*

Volume H_2 (L)	Time (min)	Average H_2 Production (L/min)	∑Time (min)	∑Average H_2 Production (L/min)
0.1	0.767	0.1304	0.767	0.1304
0.2	1.450	0.1379	0.683	0.1463
0.3	2.217	0.1353	0.767	0.1304
0.4	2.883	0.1387	0.667	0.1500
0.5	3.817	0.1310	0.933	0.1071
0.6	4.450	0.1348	0.633	0.1579
0.7	5.150	0.1359	0.700	0.1429
Average		0.1356		0.1328

Int. Journal of Integrated Engineering Vol. 18 No. 7 (2026) p. 108-122

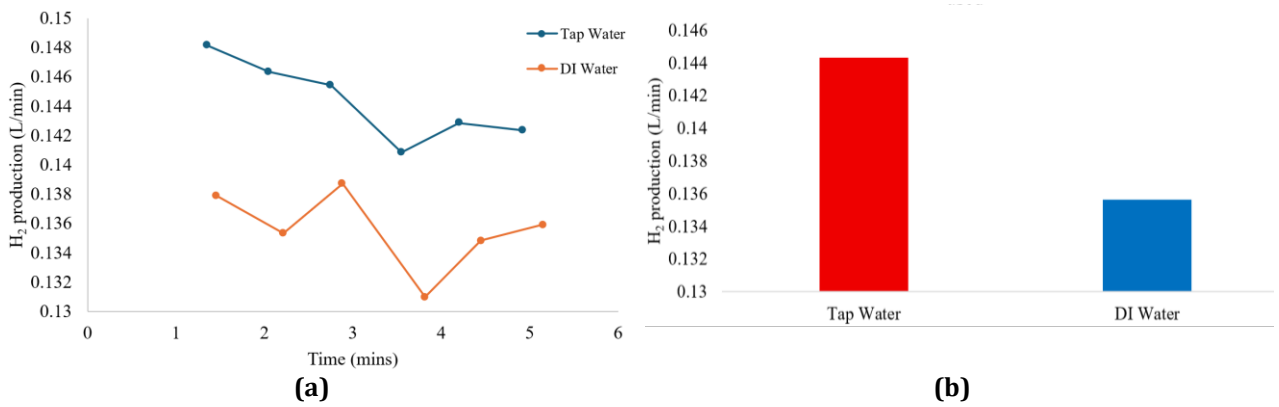


Fig. 6 *H_2 production (a) For different types of water; (b) Average value for different types of water*

The influence of water source characteristics on hydrogen production was explored through a controlled comparison between tap water and deionized (DI) water under consistent electrolysis conditions. Both water types were subjected to identical operational parameters throughout the experiment to ensure comparability. This approach allowed for a systematic evaluation of how variations in water composition might affect hydrogen production performance. As presented in Table 3 and Table 4, tap water generally produced higher hydrogen output than DI water during the tests. The system reached a peak hydrogen production rate of 0.1443 L/min with tap water, which was greater than the maximum rate recorded with DI water under the same conditions. This difference in performance was observed during the early stages of electrolysis and persisted throughout the duration of the tests. The recurring differences in hydrogen generation efficiency between the two water sources indicate that water composition can influence electrochemical behavior during electrolysis [25]. Importantly, no external electrolytes were added to either water type, ensuring that the observed outcomes were linked to the intrinsic properties of the water used. Although DI water is typically preferred in laboratory settings due to its high purity, the results from this study imply that tap water, under specific operating conditions, may provide relatively higher and more consistent hydrogen production. This observation may have practical implications for electrolysis systems where minimizing water treatment requirements is desirable for cost or operational simplicity.

No significant performance degradation or instability was observed over the test period, suggesting that basic water treatment can provide a viable alternative to high-purity DI water, especially in settings where resource efficiency and cost are important. The absence of current fluctuations, voltage drift, or visible electrode fouling during the experiments confirmed the electrochemical stability of the system using tap water. In practical terms, this implies that inexpensive water sources can be utilized effectively in hydrogen production setups without compromising long-term reliability which represent as an important consideration for low-resource or decentralized applications.

These results highlight the potential of tap water as a practical and efficient electrolyte source for hydrogen production. Its natural ionic content and low processing requirement position it as an attractive alternative to DI water, particularly when weighed against the logistical and economic challenges of maintaining ultra-pure water supplies in the field. By maintaining moderate ionic strength while minimizing harmful impurities, tap water can offer better conductivity and stable system performance compared to ultra-pure water sources, particularly in small-scale or decentralized electrolysis applications. This balance between conductivity and chemical stability ensures that tap water not only improves system efficiency but also simplifies system design by reducing reliance on chemical additives or complex pretreatment modules. Such characteristics are especially valuable in mobile, rural, or off-grid hydrogen generation units where reliability, ease of deployment, and affordability are critical.

3.2 Effect of pH Conditions on Hydrogen Production

To further explore the impact of operational parameters, hydrogen production was evaluated under different pH range of conditions from acidic (pH 5) to alkaline (pH 10). Experimental data reveal a clear correlation between pH conditions and hydrogen generation efficiency, emphasizing the critical role of electrolyte composition in electrolysis performance. The average hydrogen production rates obtained under these conditions are summarized from Table 5 – Table 10. And the graph is showed in Fig. 7.

Table 5 *Average hydrogen production rate under pH5*

Volume H_2 (L)	Time (min)	Average H_2 Production (L/min)	∑Time (min)	∑Average H_2 Production (L/min)
0.1	0.733	0.1364	0.733	0.1364
0.2	1.483	0.1348	0.750	0.1333
0.3	2.200	0.1364	0.717	0.1395
0.4	2.900	0.1379	0.700	0.1429
0.5	3.667	0.1364	0.767	0.1304
0.6	4.317	0.1390	0.650	0.1539
0.7	5.083	0.1377	0.767	0.1304
Average		0.1370		0.1343

Table 6 *Average hydrogen production rate under pH6*

Volume H_2 (L)	Time (min)	Average H_2 Production (L/min)	∑Time (min)	∑Average H_2 Production (L/min)
0.1	0.783	0.1277	0.733	0.1364
0.2	1.350	0.1481	0.567	0.1765
0.3	2.050	0.1463	0.700	0.1429
0.4	2.750	0.1455	0.700	0.1429
0.5	3.550	0.1408	0.800	0.1250
0.6	4.200	0.1429	0.650	0.1538
0.7	4.917	0.1424	0.717	0.1395
Average		0.1443		0.1453

Table 7 *Average hydrogen production rate under pH7*

Volume H_2 (L)	Time (min)	Average H_2 Production (L/min)	∑Time (min)	∑Average H_2 Production (L/min)
0.1	0.583	0.1714	0.733	0.1364
0.2	1.333	0.1500	0.750	0.1333
0.3	2.083	0.1440	0.750	0.1333
0.4	2.783	0.1437	0.700	0.1429
0.5	3.583	0.1395	0.800	0.1250
0.6	4.250	0.1412	0.667	0.1500
0.7	4.983	0.1405	0.733	0.1364
Average		0.1432		0.1368

Int. Journal of Integrated Engineering Vol. 18 No. 7 (2026) p. 108-122

Table 8 *Average hydrogen production rate under pH8*

Volume H_2 (L)	Time (min)	Average H_2 Production (L/min)	∑Time (min)	∑Average H_2 Production (L/min)
0.1	0.600	0.1667	0.733	0.1364
0.2	1.417	0.1412	0.817	0.1224
0.3	2.117	0.1417	0.700	0.1429
0.4	2.833	0.1412	0.717	0.1395
0.5	3.633	0.1376	0.800	0.1250
0.6	4.300	0.1395	0.667	0.1500
0.7	5.033	0.1391	0.733	0.1364
Average		0.1401		0.1361

Table 9 *Average hydrogen production rate under pH9*

Volume H_2 (L)	Time (min)	Average H_2 Production (L/min)	∑Time (min)	∑Average H_2 Production (L/min)
0.1	0.683	0.1463	0.733	0.1364
0.2	1.433	0.1395	0.750	0.1333
0.3	2.067	0.1452	0.633	0.1579
0.4	2.833	0.1412	0.767	0.1304
0.5	3.667	0.1364	0.833	0.1200
0.6	4.250	0.1412	0.583	0.1714
0.7	5.067	0.1382	0.817	0.1224
Average		0.1403		0.1388

Table 10 *Average hydrogen production rate under pH10*

Volume H_2 (L)	Time (min)	Average H_2 Production (L/min)	∑Time (min)	∑Average H_2 Production (L/min)
0.1	0.833	0.1200	0.733	0.1364
0.2	1.483	0.1348	0.650	0.1538
0.3	2.133	0.1406	0.650	0.1538
0.4	2.833	0.1412	0.700	0.1429
0.5	3.783	0.1322	0.950	0.1053
0.6	4.383	0.1369	0.600	0.1667
0.7	5.050	0.1386	0.667	0.1500
Average		0.1374		0.1298

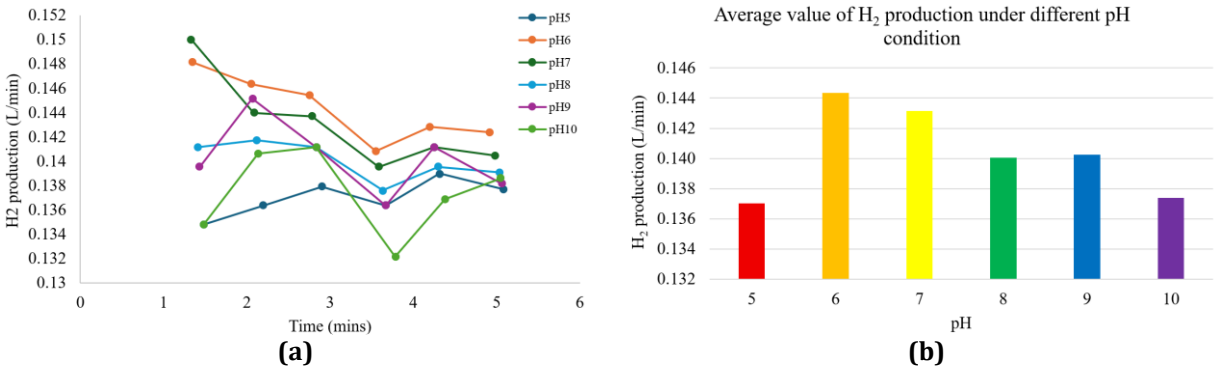


Fig. 7 *H_2 production (a) For different pH value from 5-10; (b) Average value for different pH value from 5-10*

As shown in Figure 7, hydrogen production rate follows a clear and consistent pattern across the tested pH range, with pH 6 standing out as the most efficient operating condition. At the more acidic end of the spectrum (pH 5) hydrogen output was moderate, averaging 0.1370 L/min. This reduced performance stems from higher activation energy demands for the hydrogen evolution reaction, as well as reduced electrode durability over time [26], [27]. Under strongly acidic conditions, electrode surfaces are prone to accelerated corrosion and the gradual formation of resistive oxide films, both of which slow down charge transfer at the interface and shrink the number of active catalytic sites available [5], [28]. Together, these effects suppress HER efficiency and explain the comparatively lower hydrogen yields observed at pH 5.

Hydrogen production peaks at pH 6, where the system recorded its highest average output of 0.1443 L/min. This sweet spot works because the conditions strike a natural balance which there are enough protons to drive the reaction, ion movement through the electrolyte is efficient, and the electrodes are not under excessive chemical stress. Slightly acidic, near-neutral conditions are simply friendlier to the charge-transfer process at the electrode surface, allowing gas to evolve smoothly and consistently [29]. Moving to pH 7, output holds steady at 0.1432 L/min which brings barely a drop. The fact that performance remains strong across this narrow window confirms that the weakly acidic-to-neutral range is where this PEM system truly thrives, both thermodynamically and kinetically.

Once conditions drift into alkaline territory, performance begins to fall as gradually but consistently. At pH 8, average hydrogen output eases down to 0.1401 L/min, marking the point where alkalinity starts working against the system. The way ions move through the electrolyte begins to change, overall resistance climbs, and gas bubbles start accumulating at the electrode-membrane interface. Over time, these bubbles physically block the active sites responsible for driving the reaction, interrupting what would otherwise be a steady, continuous process [30].

This downward efficiency trend becomes sequentially more pronounced at strongly alkaline values of pH 9 and pH 10, where the average outputs decrease in a regularized manner to 0.1403 L/min and 0.1374 L/min, respectively. The diminished efficiency under these higher alkaline thresholds is justified by elevated bulk electrolyte resistance, a severe scarcity of uncompleted hydronium ions (H+) forcing a shift toward slower water-reduction reaction pathways, and an increased adherence energy of gas bubbles on the electrode surface [31]. These combined penalties restrict smooth ion transport, mask the active electrochemical surface area, and increase charge-transfer resistance, generating the uniform decline in overall hydrogen generation shown in the regularized plots.

In summary, the regularized experimental evidence demonstrates that precise control of electrolyte pH is critical for maximizing water electrolysis performance. Keeping the system within the near-neutral window, particularly around pH 6, keeps activation losses low, stabilizes charge transfer, and prevents bubble buildup from masking the electrode surface. For anyone aiming at high-efficiency, long-running hydrogen production, this is the operating zone to target.

3.3 Summary

The comprehensive experimental results of this study clearly demonstrate that both the purity of the water source and the specific pH level of the electrolyte play pivotal roles in dictating the overall efficiency of hydrogen production via water electrolysis. The comparative evaluation between standard tap water and high-purity deionized (DI) water brings to light the critical importance of intrinsic ionic content within the electrochemical environment. Contrary to the common reliance on ultra-pure water, tap water significantly outperformed DI water in terms of the hydrogen production rate. The natural mineral and ionic composition present in tap water actively facilitates superior charge transport across the electrodes, effectively reduces the system's internal ohmic resistance, and supports a more consistent and stable current flow throughout the electrolysis process.

Consequently, the laboratory-scale system utilizing tap water achieved a notable peak hydrogen production rate of 0.1443 L/min, decisively surpassing the 0.1356 L/min output recorded for DI water under identical operational parameters. Moreover, the complete absence of observable electrode fouling or short-term performance degradation strongly indicates that basic, low-intensity water treatment is entirely sufficient to mitigate harmful impurities that might otherwise compromise the system's integrity. This pivotal finding positions unpurified or minimally processed tap water as a highly practical, scalable, and cost-effective alternative, particularly beneficial for the deployment of decentralized or off-grid hydrogen production systems where advanced water purification infrastructure is unavailable or economically unviable.

In parallel to the water source findings, the systematic investigation into varying electrolyte pH conditions revealed a corresponding trend in performance optimization. The empirical data showed that the hydrogen evolution rate reached its absolute maximum at a slightly acidic pH of 6, exactly matching the optimal peak performance observed with the standard tap water trials (0.1443 L/min). Operating within this specifically defined, weakly acidic to near-neutral range affords the electrolysis system a highly favorable electrochemical balance: it ensures abundant proton availability required to drive the Hydrogen Evolution Reaction (HER) forward, maintains excellent ionic conductivity, and substantially mitigates the risk of long-term electrode degradation. Conversely, deviating from this optimal window toward either extreme resulted in measurable performance penalties. Strongly acidic conditions (pH 5) introduced increased reaction overpotentials and accelerated the risk of structural corrosion, which inherently hindered catalytic efficiency. Similarly, shifting toward strongly alkaline environments (pH 9–10) yielded reduced hydrogen production rates. In these alkaline regimes, the system experienced amplified internal resistance, hindered hydroxide ion transport, and severe gas bubble accumulation at the electrode-electrolyte interface. This bubble adherence physically obstructed access to the active catalytic sites, severely impairing continuous mass transfer and localized reaction kinetics.

Taken together, these foundational findings emphatically underscore the synergistic impact that precisely controlled water quality and optimized electrolyte pH have on sustainable hydrogen production. The strategic combination of utilizing moderately conductive tap water and operating under near-neutral pH conditions cultivates an optimal electrochemical environment tailored for efficient, robust, and stable hydrogen generation. This specific operational matrix naturally enhances overall system conductivity, rigorously protects the structural and chemical integrity of the electrodes, and ensures highly effective charge transfer with minimal energy loss. As a result, this integrated approach is exceptionally well-suited for transitioning from laboratory-scale setups to broader practical applications. By significantly lowering the barrier to entry regarding water purity requirements and defining a safe, highly productive pH operating window, these insights offer a tangible pathway toward improving resource efficiency, lowering operational costs, and extending the long-term performance lifespan of advanced, membrane-based electrolysis technologies.

Acknowledgement

This research was supported by Universiti Tun Hussein Onn Malaysia through Tier 1 (VOT Q369) and Geran Penyelidikan Pasca Siswazah (VOT J156).

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Frederick T.T.N, Jais Lias;* ***data collection:*** *Frederick T.T.N, Jais Lias, M.A.H Hamdan, Kim Seng Ng;* ***analysis and interpretation of results:*** *Shazleen Ahmad Ramli, M.K. Ahmad, MH. MAMAT, M.Y. Ahmad;* ***draft manuscript preparation:*** *Frederick T.T.N, M.K. Ahmad. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] International Renewable Energy Agency (IRENA), *Hydrogen: a Renewable Energy Perspective*, no. September. 2019. [Online]. Available: https://irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective

[2] K. Saidi, M. Mikou, and M. Kaddami, "Hydrogen Production via Alkaline Water Electrolysis Using Cathode Elaborated by Zinc-Manganese Alloy," vol. 02004, pp. 4–7, 2025.

[3] M. Shviro, S. Y. Kang, F. D. Campos, V. Larson, S. Maurya, and D. P. Leonard, "Standardization and best practices in single-cell testing for liquid alkaline water electrolysis," *Front. Energy Res.*, vol. 13, no. April, pp. 1–9, 2025, doi: 10.3389/fenrg.2025.1554086.

[4] G. K. Gebremariam, A. Z. Jovanović, and I. A. Pašti, "The Effect of Electrolytes on the Kinetics of the Hydrogen Evolution Reaction," *Hydrog.*, vol. 4, no. 4, pp. 776–806, 2023, doi: 10.3390/hydrogen4040049.

[5] J. H. Kim, H. J. Jo, S. M. Han, Y. J. Kim, and S. Y. Kim, "Recent advances in electrocatalysts for anion exchange membrane water electrolysis: design strategies and characterization approaches," *Energy Mater.*, vol. 5, no. 8, 2025, doi: 10.20517/energymater.2024.290.

[6] R. Amore-domenech, I. Carrillo, E. Navarro, and T. J. Leo, "Alkaline Electrolysis for Hydrogen Production at Sea :," pp. 1–13, 2023.

[7] K. E. Y. References, "Alkaline Water Electrolysis for Green Hydrogen Production," 2024, doi: 10.1021/acs.accounts.3c00709.

[8] Y. Luo and R. Su, "Environmental Impact of Waste Treatment and Synchronous Hydrogen Production: Based on Life Cycle Assessment Method," *Toxics*, vol. 12, no. 9, p. 652, 2024, doi: 10.3390/toxics12090652.

[9] H. Becker, J. Murawski, D. V. Shinde, I. E. L. Stephens, G. Hinds, and G. Smith, "Impact of impurities on water electrolysis: a review," *Sustain. Energy Fuels*, vol. 7, no. 7, pp. 1565–1603, 2023, doi: 10.1039/d2se01517j.

[10] J. Huang *et al.*, "A universal pH range and a highly efficient Mo2C-based electrocatalyst for the hydrogen evolution reaction," *J. Mater. Chem. A*, vol. 8, no. 38, pp. 19879–19886, 2020, doi: 10.1039/d0ta07091b.

[11] P. Li, Y. L. Jiang, Y. Men, Y. Z. Jiao, and S. Chen, "Kinetic cation effect in alkaline hydrogen electrocatalysis and double layer proton transfer," *Nat. Commun.* , vol. 16, no. 1, 2025, doi: 10.1038/s41467-025-56966-9.

[12] P. S. Lamoureux, A. R. Singh, and K. Chan, "PH Effects on Hydrogen Evolution and Oxidation over Pt(111): Insights from First-Principles," *ACS Catal.*, vol. 9, no. 7, pp. 6194–6201, 2019, doi: 10.1021/acscatal.9b00268.

[13] L. H. Prado, S. Virtanen, N. Weineck, A. Ghicov, and F. Kessler, "How to perform corrosion experiments for proton exchange membrane water electrolysis bipolar plates," *J. Power Sources*, vol. 613, no. April, p. 234815, 2024, doi: 10.1016/j.jpowsour.2024.234815.

[14] K. Dastafkan *et al.*, "Operando monitoring of gas bubble evolution in water electrolysis by single high-frequency impedance," *EES Catal.*, vol. 1, no. 6, pp. 998–1008, 2023, doi: 10.1039/d3ey00182b.

[15] L. R. Winter, N. J. Cooper, B. Lee, S. K. Patel, L. Wang, and M. Elimelech, "Mining Nontraditional Water Sources for a Distributed Hydrogen Economy," *Environ. Sci. Technol.*, vol. 56, no. 15, pp. 10577–10585, 2022, doi: 10.1021/acs.est.2c02439.

[16] L. Wu *et al.*, "Direct seawater electrolysis for green hydrogen production: electrode designs, cell configurations, and system integrations," *Energy Environ. Sci.*, pp. 4596–4624, 2025, doi: 10.1039/d5ee01093d.

[17] J. Knöppel *et al.*, "On the limitations in assessing stability of oxygen evolution catalysts using aqueous model electrochemical cells," *Nat. Commun.*, vol. 12, no. 1, pp. 1–9, 2021, doi: 10.1038/s41467-021-22296-9.

[18] T. W. LeBaron, R. Sharpe, and K. Ohno, "Electrolyzed–Reduced Water: Review II: Safety Concerns and Effectiveness as a Source of Hydrogen Water," *Int. J. Mol. Sci.*, vol. 23, no. 23, 2022, doi: 10.3390/ijms232314508.

[19] A. Rajesh, "Effect of Electrolyte Concentration on the Efficiency of Electrochemical Cells in India," *J. Chem.*, vol. 3, no. 2, pp. 31–41, 2024, doi: 10.47672/jchem.2402.

[20] K. Zhang *et al.*, "Status and perspectives of key materials for PEM electrolyzer," *Nano Res. Energy*, vol. 1, no. 3, pp. 1–8, 2022, doi: 10.26599/NRE.2022.9120032.

[21] A. Ganguli and V. Bhatt, "Hydrogen production using advanced reactors by steam methane reforming: A review," *Front. Therm. Eng.*, vol. 3, no. April, pp. 1–15, 2023, doi: 10.3389/fther.2023.1143987.

[22] W. H. Chiang, S. J. Lin, and J. S. Wu, "A Simple Approach for Regenerating Electrolyzed Hydrogen Production Using Non-De-Ionized Water Sources," *Materials (Basel).*, vol. 16, no. 23, pp. 1–11, 2023, doi: 10.3390/ma16237382.

[23] H. Li, J. Guo, Z. Li, and J. Wang, "Research Progress of Hydrogen Production Technology and Related Catalysts by Electrolysis of Water," *Molecules*, vol. 28, no. 13, pp. 1–18, 2023, doi: 10.3390/molecules28135010.

[24] M. R. Alex Badgett, Joe Brauch, Amogh Thatte, Rachel Rubin, Christopher Skangos, Xiaohua Wang, Rajesh Ahluwalia, Bryan Pivovar, "Updated Manufactured Cost Analysis for PEM Water Electrolyzers," 2024. [Online]. Available: https://docs.nrel.gov/docs/fy24osti/87625.pdf

[25] J. Lee, S. A. Lee, T. H. Lee, and H. W. Jang, "Unlocking the potential of chemical-assisted water electrolysis for green hydrogen production," *Ind. Chem. Mater.*, vol. 3, no. 3, pp. 277–310, 2025, doi: 10.1039/d4im00163j.

[26] Y. Zhu *et al.*, "Facilitating alkaline hydrogen evolution reaction on the hetero-interfaced Ru/RuO2 through Pt single atoms doping," *Nat. Commun.*, vol. 15, no. 1, 2024, doi: 10.1038/s41467-024-45654-9.

[27] F. Bao *et al.*, "Understanding the Hydrogen Evolution Reaction Kinetics of Electrodeposited Nickel-Molybdenum in Acidic, Near-Neutral, and Alkaline Conditions," *ChemElectroChem*, vol. 8, no. 1, pp. 195–208, 2021, doi: 10.1002/celc.202001436.

[28] R. Ben Slama, "Hydrogen Production by Water Electrolysis Effects of the Electrodes Materials Nature on the Solar Water Electrolysis Performances," *Nat. Resour.*, vol. 04, no. 01, pp. 1–7, 2013, doi: 10.4236/nr.2013.41001.

[29] H. Zhang, X. Guo, W. Liu, D. Wu, D. Cao, and D. Cheng, "Regulating surface composition of platinum-copper nanotubes for enhanced hydrogen evolution reaction in all pH values," *J. Colloid Interface Sci.*, vol. 629, pp. 53–62, Jan. 2023, doi: 10.1016/J.JCIS.2022.08.116.

[30] B. Ross, S. Haussener, and K. Brinkert, "Impact of Gas Bubble Evolution Dynamics on Electrochemical Reaction Overpotentials in Water Electrolyser Systems," *J. Phys. Chem. C*, 2025, doi: 10.1021/acs.jpcc.5c00220.

[31] C. Wu, J. Liu, and Y. Tan, "Transition metal sulfides in alkaline hydrogen evolution electrocatalysis: Re-exploring their structure and composition evolution and its correlation with activity," *Nano Res.*, vol. 18, no. 3, pp. 1–16, 2025, doi: 10.26599/NR.2025.94907240.