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Water Quality Effects on PEM Electrolyzer Performance:Short-Term Comparative Assessment of Four Common Sources

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Abstract

Water quality requirements are a major barrier to proton exchange membrane (PEM) electrolyser deployment in settings where ultra-pure water is costly or unavailable. This study evaluates a small-scale PEM electrolyser operated with four commonly accessible water sources: distilled water, municipal tap water, packaged sachet water and borehole water. For each water type, three repeated tests were conducted and hydrogen production time, specific energy consumption (SEC) and electrical characteristics were measured under identical operating conditions. In addition, the physicochemical properties of the water sources, including electrical conductivity, total dissolved solids, pH and major ions, were characterised to support interpretation of performance trends. Performance differences between water types were modest. Hydrogen production times ranged from 13.3 to 15 minutes (≈11% spread), SEC from 3.82 to 4.14 Wh/L (≈8%) and operating voltage from 2.06 to 2.07 V (<1%). Contrary to expectation, distilled water produced hydrogen most slowly and was not the most energy efficient. Borehole water achieved the lowest SEC (3.82 Wh/L), while all non-distilled sources produced hydrogen about 7–11% faster than distilled water, consistent with their higher measured ionic conductivity. Visual inspection showed no electrode fouling during testing. These results indicate that, in the short term, non-ideal but readily available water sources such as tap and borehole water can support acceptable hydrogen production in intermittent PEM electrolyser operation. However, the short test duration, approximately one hour per water type, limits conclusions regarding long-term durability, which will require extended monitoring and ageing studies.

Keywords: Pem Electrolyzer, Water Quality, Hydrogen Production, Off-Grid Energy, West Africa, Borehole Water

Introduction

Note that hydrogen is increasingly being explored as a clean energy carrier for cutting emissions from transport and industry [1-5]. In a fuel cell (FC), it combines with oxygen to produce electricity, with water as the only by-product [6-8]. This makes it a promising option for reducing greenhouse gas emissions. Proton exchange membrane (PEM) electrolysers have become one of the main technologies for small-to-large-scale, distributed hydrogen production [9-13]. They are compact, relatively efficient and can operate over a wide range of loads, which makes them suitable for use with variable renewable sources such as solar and wind power [10,14-16].

In off-grid settings, hydrogen systems could help tackle energy access challenges [17-21]. Many rural communities have little or no reliable grid electricity but receive ample solar radiation or, in some cases, wind. Small PEM electrolysers coupled to local renewable generators can therefore provide on-site hydrogen for cooking, lighting or FC applications. A key obstacle, however, is the strict water quality requirement imposed by PEM technology [22,23].

Explain that PEM electrolysers are highly sensitive to impurities in the feed water [24-28,12]. Manufacturers therefore specify tight limits on water quality. In many cases, industry guidelines call for total dissolved solids below 10 mg/L and electrical conductivity under 5 μS/cm, which in practice implies the use of distilled or deionised water [23,29]. These specifications are primarily intended to ensure long-term durability and stable operation over thousands of operating hours, rather than short-term performance during intermittent use. In off-grid contexts, such purity levels are often difficult or too costly to achieve. Rural communities usually depend on locally available sources such as boreholes, rainwater, municipal tap water or packaged drinking water, all of which contain varying concentrations of dissolved minerals and other impurities.

A practical question then follows: can PEM electrolysers operate reliably on these non-ideal water sources in the short term, and what effect does this have on their immediate performance? This issue is especially important in developing regions, where water treatment infrastructure is limited and high-purity water may not be readily available. Water purification accounts for approximately 22% of PEM electrolyser system costs and creates deployment constraints in water-scarce regions [12,22,23].

Laboratory studies have systematically investigated cation contamination effects using controlled additions of Na^+, K^+, Mg^{2+} and Ca^{2+} to pure water over test durations ranging from hours to hundreds of hours [26,12,30]. These studies confirm that cation impurities reduce membrane conductivity and alter reaction kinetics, with divalent ions generally exerting stronger effects than monovalent ions. However, most experimental work relies on synthetic contamination under controlled laboratory conditions, rather than testing locally available water sources as encountered in real deployment contexts.

In resource-limited settings, the practical questions differ. Before investing in extended durability studies, a basic feasibility question must be answered: can PEM electrolysers operate at all with locally available water sources, or do impurities cause immediate failure? If non-ideal water leads to rapid performance collapse within the first hour, long-term testing becomes irrelevant.

This study addresses this preliminary question through short-term comparative testing. Four commonly available water sources were systematically compared: distilled water (control), municipal tap water, packaged sachet water and borehole water. Each source was tested in triplicate to assess immediate operational viability and short-term performance characteristics.

The goal is not to validate long-term deployment strategies, but rather to screen which water sources warrant further investigation. If certain water types show immediate incompatibility—such as rapid voltage increases, visible fouling or system failure—they can be eliminated from consideration. Conversely, water sources that demonstrate stable short-term operation become candidates for extended durability studies.

The Aims of this Work are to:

- Compare hydrogen production performance for four commonly available water sources under controlled experimental conditions.
- Quantify differences in energy efficiency, expressed as SEC, between water types over three consecutive test cycles.
- Examine whether simple visual inspection of the electrodes relates to the observed performance differences.
- Offer evidence-based guidance on suitable water sources for PEM electrolyser deployment in resource-limited settings.

This study is set in West Africa, where limited water availability and unreliable electricity place real constraints on the use of hydrogen technologies [31-34]. In many rural communities, boreholes are the main water source, while the quality of municipal tap water can vary widely from place to place. Packaged sachet water is now the most common drinking water in towns and cities, yet its suitability for technical applications such as electrolysis has received little attention. Understanding how these locally available water sources influence PEM electrolyser performance is therefore essential for realistic planning and deployment of hydrogen systems in the region.

The rest of the paper is structured as follows. Section 2 describes the experimental setup, water sources, testing procedure and data analysis approach. Section 3 presents the comparative results, including hydrogen production time, energy efficiency, electrical behaviour and visual electrode inspection observations. Section 4 discusses the implications of these findings and outlines the main limitations. Section 5 summarises the key conclusions and proposes directions for future work.

Materials and Methods

Experimental Setup

In this experiment, a Horizon Educational Solar Hydrogen Science Kit obtained from was used, as illustrated in Figure 1. The kit contains a small PEM electrolyser intended for educational laboratory work. In electrolysis mode it splits water into hydrogen and oxygen. Hydrogen is collected by water displacement in a transparent graduated tube with 2 mL markings. The oxygen side has a similar tube but only the hydrogen volume was recorded [35].

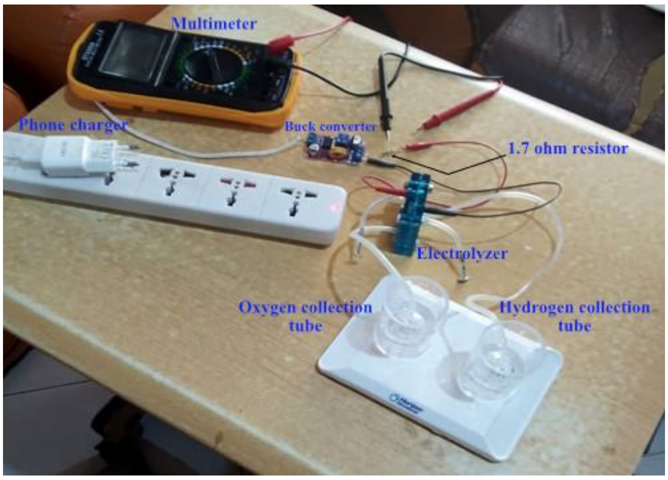


Figure 1. Experimental Setup Experimental Setup Showing the Pem Electrolyser, Hydrogen Collection Tube, dc Buck Converter, 1.7 ω Series Resistor and Multimeter Arrangement Used for the Measurements.

Electrical power was supplied by a phone charger connected to a DC–DC buck converter. The USB cable of the charger was cut open to expose the red and black conductors, which were fixed to the input terminals of the converter. The buck converter output was set to 2.1 V, which lies within the electrolyser's specified operating range of 1.8–3.0 V [35]. A mains-powered phone charger was used as the input source instead of the kit's solar panel to avoid variations in sunlight and to keep the electrical conditions the same for all tests.

Current was measured indirectly using a 1.7 Ω resistor connected in series between the positive output of the converter and the electrolyzer. A digital multimeter measured the voltage drop across this resistor. We then applied Ohm's law ($V = IR$). With $R = 1.7\ \Omega$, the operating current was calculated as $I= V_{resistor}/1.7$. No separate ammeter was needed. The circuit remained intact.

The voltage supplied to the electrolyser (cell voltage) was measured at the buck converter output terminals. This was done because the kit's banana plugs fit tightly into the electrolyser housing, leaving no exposed metal for direct probing. At each reading, the multimeter was switched between the converter output and the series resistor so that both the cell voltage and the resistor voltage could be recorded in turn.

Water Sources

Four water types were chosen to reflect water sources that are commonly available in the study area:

- Distilled water (baseline)
- Sterile water for injection (pharmaceutical-grade distilled water) was bought from a local pharmacy in Wa and used as the control.
- Tap water
- Municipal tap water was taken from a household connection supplied by Ghana Water Company Limited in Wa, representing typical domestic water quality.
- Sachet water
- Commercial drinking water sold in sealed plastic sachets (pure wate) was purchased from local vendors. This is the most widely consumed drinking water in both urban and rural Ghana.
- Borehole water
- Deep groundwater from a borehole in a peri-urban area of Wa was collected in a clean container. The borehole, estimated to be more than 30 m deep, is fitted with basic filtration and is used for drinking, cooking, etc. by local residents. Natural filtration through soil and rock provides some treatment but dissolved minerals such as calcium, magnesium and iron remain [36,37]. No laboratory treatment or extra filtration was applied before testing.

All water samples were used at room temperature without heating, pH adjustment or chemical modification. Fresh tap and borehole samples were collected within 24 hours of use; distilled water was taken from newly opened containers and sachet water was used immediately after opening.

Experimental Procedure

Each water type was tested in triplicate (n = 3) on consecutive days under similar ambient conditions. All experiments were carried out in the morning, between 7:00 and 11:00 a.m., to limit temperature variations. The hydrogen and oxygen collection tubes were first filled with sterile water. Only the internal chamber of the PEM electrolyser received the water sample under investigation. Before each cycle, the electrolyzer was drained by inversion.

The cell was then flushed with fresh sterile water and drained again. To minimise any carry-over from the previous sample, the electrolyser was filled with sterile water and operated for one minute at the set voltage of 2.1 V. After this short flush, the cell was drained and refilled with the new sample. For each cycle, the selected water sample (distilled, sachet, tap or borehole) was added to the electrolyzer chamber. Trapped air bubbles were released by tapping and tilting the unit gently.

The power supply was then switched on and measurements began immediately. Voltage at the buck converter output and the voltage drop across the 1 Ω resistor were recorded at one-minute intervals using a digital multimeter. Hydrogen production was monitored at the same intervals by reading the displaced water level in the calibrated hydrogen collection tube. This continued until the hydrogen volume reached the 16 mL mark, corresponding to complete water displacement from the collection tube. At this point, no further volume increase could be measured despite continued gas production (evidenced by bubbles venting from the tube outlet).

After each cycle, the power supply was switched off and the flushing procedure was repeated. The three-cycle sequence was completed for one water type before moving to the next. Photographs of the PEM electrolyzer, using a smartphone camera, were taken at the end of the three cycles for each water type and again after repeating the distilled water test at the end of all experiments. The standardized endpoint of 16 mL hydrogen production was used for all tests, allowing fair comparison of the time and energy required to reach this fixed output volume. SEC and production rate could then be calculated on a normalized basis.

Water Chemistry Characterisation

To support interpretation of the electrolysis results, the physicochemical properties of the water sources were characterised prior to testing. Samples of distilled water, municipal tap water, packaged sachet water and borehole water were submitted for analysis at the Ghana Water Company laboratory in Wa. Electrical conductivity, total dissolved solids (TDS) and pH were measured using standard water quality testing procedures. Major ionic constituents, including calcium, magnesium, sodium, potassium and chloride, were also determined. Water hardness was reported as $CaCO_3$. The measured water chemistry values were used solely to contextualise short-term performance trends and were not employed to modify operating conditions or control variables during electrolysis testing.

Data Analysis

Raw data from each test consisted of time-series measurements of voltage, current and hydrogen volume. From these primary measurements, several derived performance metrics were calculated:

Instantaneous Power

$$P(t) = V_{\text{cell}}(t) \times I(t)\#(1)$$

where:

- P(t) = instantaneous power at time t, W.
- V_{cell} (t) = cell voltage at time t, V.
- I(t) = current at time t, A.

Cumulative Energy Input

Total energy was calculated using the trapezoidal rule for numerical integration:

$$E_{\text{total}} = \sum_{i=1}^{n-1} \left[\frac{P_i + P_{i+1}}{2}\right] \times \Delta t\#(2)$$

where:

E_{total} = total cumulative energy input, Wh.
P_i = instantaneous power at measurement i, W.
P_{i+1} = instantaneous power at measurement i+1, W.
Δt = time interval between measurements, $\mathrm{h} = \frac{1}{60}$ h for 1-minute intervals.
n = total number of measurements up to 16 mL H_2 endpoint.

The summation was performed only up to the time when 16 mL hydrogen volume was reached.

Specific Energy Consumption (SEC)

$$\text{SEC} = \frac{E_{\text{total}}}{V_{\mathrm{H_2}}}\#(3)$$

where:

- SEC = specific energy consumption (Wh/L).
- E_{total} = total energy input from Equation 2 (Wh).
- V_{H2} = hydrogen volume produced (L) = 0.016 L (equivalent to 16 mL).

SEC shows how much energy is needed per unit volume of hydrogen (Yoshimura et al., 2022). It serves as the main efficiency metric (Rodriguez et al., 2024). Lower values mean better efficiency.

Hydrogen Production Rate

$$\text{Rate} = \frac{V_{\text{H}_2}}{t_{\text{endpoint}}} \#(4)$$

where:

- Rate = hydrogen production rate (mL/min).
- V_{H2} = hydrogen volume at endpoint = 16 mL.
- $t_{endpoint}$ = time when 16 mL hydrogen was reached (minutes)

Higher production rate indicates faster hydrogen generation.

Average Electrical Parameters

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \#(5)$$

where:

- $\bar{X}$ = mean value of parameter X
- X_i = measured value at time point i
- n = total number of measurements

These averages characterize the typical operating conditions during each test.

Statistical Measures

Each water type had three replicate tests. This gave three values per metric for calculations:

Mean

$$\mu = \frac{1}{k}\sum_{j=1}^{k} x_j \#(6)$$

where:

- μ = mean value across replicates.
- x_j = value from replicate test j.
- k = number of replicate tests = 3.

Standard Deviation

$$\text{SD} = \sqrt{\frac{\sum_{j=1}^{k}(x_j - \mu)^2}{k-1}} \#(7)$$

Coefficient of Variation (CV)

$$\text{CV} = \left(\frac{\text{SD}}{\mu}\right) \times 100\% \#(8)$$

The CV serves as a measure of reproducibility. Lower CV values indicate more precise and consistent measurements across replicate tests.

Relative Performance

$$\Delta(\%) = \left[\frac{\text{Value}_{\text{test}} - \text{Value}_{\text{distilled}}}{\text{Value}_{\text{distilled}}}\right] \times 100\%\#(9)$$

where:

- $\Delta(\%)$ = relative difference.
- $\text{Value}_{\text{test}}$ = mean value for test water type.
- $\text{Value}_{\text{distilled}}$ = mean value for distilled water (baseline).

Negative percentages indicate better performance than distilled water whereas positive percentages indicate worse performance.

Analytical Tools

All calculations were performed using PTC Mathcad Prime. Graphs were generated using Python (matplotlib library).

Results

Overview of Performance Metrics

Figure 2 shows the main performance metrics for all four water types. Values appear as mean ± standard deviation. Bar charts include error bars. All sources successfully produced hydrogen. Every run reached the 16 mL target. Average times ranged from 13.3 to 15 minutes.

This represents an 11% spread between the fastest and slowest water types. SEC varied from 3.82 to 4.14 Wh/L, an 8% difference. Operating voltage remained nearly identical across all water types, varying by less than 1% (2.06–2.07 V). Average current ranged from 0.143 to 0.156 A, corresponding to approximately 9% variation.

The CV for SEC was 2.4% for distilled water, 2.3% for tap water, 1.2% for sachet water and 4.3% for borehole water. Voltage measurements also showed CV values below 5% for all water types.

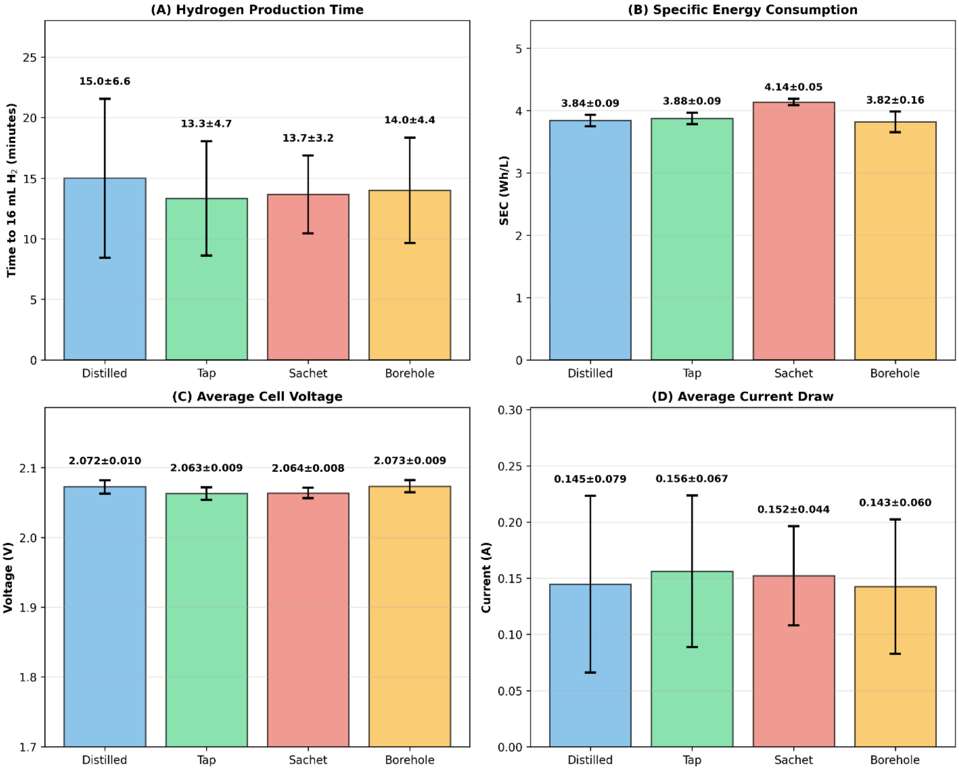


Figure 2. Summary Performance Comparison across all four Water types Showing Mean Values with Standard Deviation Error Bars (n=3). (a) Time Required to Produce 16 ml Hydrogen. (b) sec. (c) Average Cell Voltage. (d) Average Current Draw. Error Bars Represent ±1 Standard Deviation. Values are Labelled on each Bar. This Figure Presents all Measured Performance Metrics in Visual Format for Direct Comparison Across Water Types.

Hydrogen Production Time

Figure 3A presents hydrogen production time as box plots showing the distribution of the three replicate tests for each water type.

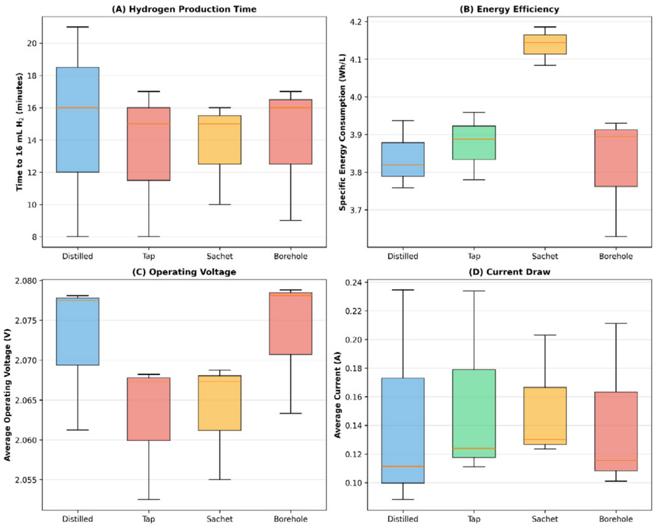


Figure 3. Comparative Performance Metrics for Pem Electrolyzer Operation with four Water Sources. Box Plots Show Distribution of three Replicate Tests (n=3) for each Water type. (a) Time Required to Produce 16 ml Hydrogen. (b) sec. (c) Average Cell Voltage. (d) Average Current Draw. Box Boundaries Represent 25th and 75th Percentiles, Centre Lines Show Median Values and Whiskers Extend to Minimum and Maximum Values.

Distilled water required an average of 15.0 ± 6.6 minutes to produce 16 mL hydrogen. Tap water showed an average production time of 13.3 ± 4.7 minutes. Sachet water required 13.7 ± 3.2 minutes, while borehole water required 14.0 ± 4.4 minutes. When ranked by production speed, tap water produced hydrogen fastest, followed by sachet water, borehole water and distilled water.

Energy Efficiency

Figure 3B shows the SEC values for each water type. Borehole water recorded the lowest SEC at 3.82 ± 0.16 Wh/L. Distilled water had a SEC of 3.84 ± 0.09 Wh/L. Tap water recorded 3.88 ± 0.09 Wh/L, while sachet water recorded the highest SEC of 4.14 ± 0.05 Wh/L. In terms of energy efficiency, the water types ranked as borehole water, distilled water, tap water and sachet water.

Electrical Characteristics

Figure 3C and Figure 3D show the average cell voltage and current for each water type. Average operating voltages were 2.063 V for tap water, 2.064 V for sachet water, 2.072 V for distilled water and 2.073 V for borehole water. The maximum difference between any two values was approximately 10 mV. Average current values were 0.143 A for borehole water, 0.145 A for distilled water, 0.152 A for sachet water and 0.156 A for tap water.

Test Progression Patterns

Figure 4 shows how performance metrics evolved across the three consecutive tests for each water type.

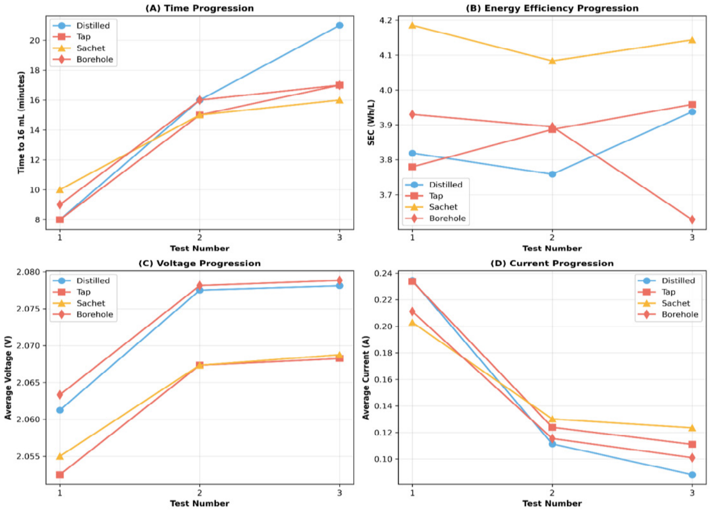


Figure 4. Performance Metric Progression across three Consecutive Tests for each Water type, Illustrating Electrode Conditioning Effects. (A) Hydrogen Production Time. (B) Specific Energy Consumption. (C) Average Cell Voltage. (D) Average Current Draw. All Water

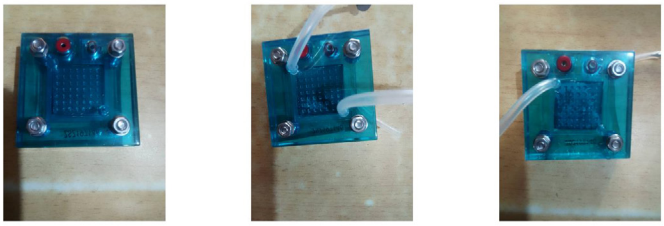
For hydrogen production time, all four water types exhibited similar progression patterns. Distilled water production times progressed from 8.0 to 16.0 to 21.0 minutes. Tap water progressed from 8.0 to 15.0 to 17.0 minutes. Sachet water progressed from 10.0 to 15.0 to 16.0 minutes. Borehole water progressed from 9.0 to 16.0 to 17.0 minutes.

SEC values for distilled water progressed from 3.82 to 3.76 to 3.94 Wh/L. Tap water SEC values progressed from 3.78 to 3.89 to 3.96 Wh/L. Sachet water SEC values progressed from 4.19 to 4.08 to 4.14 Wh/L. Borehole water SEC values progressed from 3.93 to 3.89 to 3.63 Wh/L.

Average cell voltage increased across successive tests for all water types. Distilled water voltage progressed from 2.061 to 2.078 V. Tap water progressed from 2.052 to 2.068 V. Sachet water progressed from 2.059 to 2.070 V. Borehole water progressed from 2.067 to 2.075 V. Average current generally decreased from Test 1 to Test 3 for all water types.

Visual Electrode Assessment

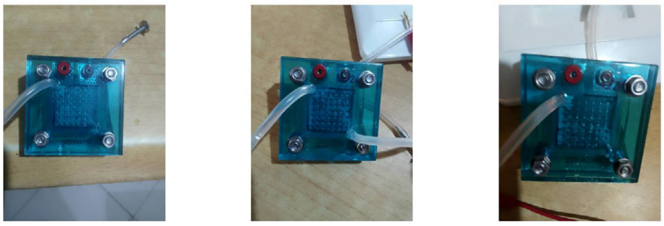
Figure 5 shows photographs of the PEM electrolyser taken after three tests for each water type and after completion of all twelve tests. For distilled water, electrodes appeared unchanged after testing. For tap water, no visible deposits or colour changes were observed. For sachet water, electrode surfaces appeared clean with no visible fouling. For borehole water, no mineral deposits or staining were observed. After completion of all twelve tests, electrodes remained visually clean and indistinguishable from their initial condition.



A) Before Testing (Pristine Electrode)

B) After Distilled Water (3 tests, ~45 min total)

C) After Tap Water (3 tests, ~40 min total)



D) After Sachet Water (3 tests, ~41 min total)

E) After Borehole Water (3 tests, ~42 min total)

F) After All Testing (Distilled re-test, 12 total tests)

Figure 5. Visual Electrode Assessment after Testing with Different Water types. (a) Pristine Electrodes before any Testing. (b) After three Distilled Water Tests (~45 min total Operation). (c) After three tap Water Tests (~40 min). (d) After three Sachet Water tests (~41 min). (e) After three Borehole Water tests (~42 min). (f) After Complete Experimental Sequence Including Distilled Water Re-test (12 total tests, ~3 hours Cumulative Operation). No Visible Deposits, Discoloration or Fouling observed across any Water type despite Measurable Performance Differences.

Relative Performance Comparison

Table 1 summarises the relative performance of each water type compared with distilled water. Tap water showed an 11.1% reduction in hydrogen production time and a 1.0% increase in SEC relative to distilled water. Sachet water showed an 8.9% reduction in production time and a 7.8% increase in SEC. Borehole water showed a 6.7% reduction in production time and a 0.5% reduction in SEC. Voltage differences relative to distilled water were below 1% for all water types.

Water Type	Time change (%)	SEC change (%)	Voltage Change (%)
Tap	-11.1 (Faster)	+1.0 (Slightly less efficient)	-0.43 (Lower)
Sachet	-8.9 (Faster)	+7.8 (Less efficient)	-0.39 (Lower)
Borehole	-6.7 (Faster)	-0.5 (More efficient)	+0.05 (Similar)

Table 1. Relative Performance vs. Distilled Water

Note: Negative % = better than distilled; Positive % = worse than distilled

Reproducibility Assessment

SEC showed CV values ranging from 1.2% to 4.3% across all water types. Voltage CV values ranged from 2.3% to 4.2%. Production time CV values ranged from 23.5% to 43.7%. Current CV values ranged from 26.8% to 50.3%.

Physicochemical Properties of Water Sources

Table 2 summarises the measured physicochemical properties of the four water sources used in the PEM electrolyser tests: distilled water, municipal tap water, packaged sachet water and borehole water.

Parameter	Unit	Distilled Water	Tap Water	Sachet Water	Borehole Water
Electrical conductivity	$\mu S\ cm^{-1}$	4.55	275	25.10	35.3
Total dissolved solids (TDS)	$mg\ L^{-1}$	2.27	137.50	12.55	17.65
pH	–	5.60	6.60	6.00	5.60
Calcium (Ca^{2+})	$mg\ L^{-1}$	2.0	60.0	6.4	8.0
Magnesium (Mg^{2+})	$mg\ L^{-1}$	0.0	10.0	2.0	6.0
Chloride (Cl^-)	$mg\ L^{-1}$	40.0	30.0	12.0	28.0
Water hardness (as $CaCO_3$)	$mg\ L^{-1}$	2	70	6	14
Sodium (Na^+)	$mg\ L^{-1}$	10.52	7.89	3.15	3.68
Potassium (K^+)	$mg\ L^{-1}$	2.10	1.57	0.63	0.73

Table 2.Physicochemical Properties of Water Sources Used in Pem Electrolyser Tests

Electrical conductivity varied widely across the water types. Distilled water showed the lowest conductivity at 4.55 μS/cm. Tap water had the highest conductivity at 275 μS/cm. Sachet water and borehole water recorded conductivities of 25.10 μS/cm and 35.3 μS/cm respectively.

Total dissolved solids (TDS) followed a similar trend. Distilled water recorded a TDS of 2.27 mg/L. Tap water had the highest TDS at 137.50 mg/L. Sachet water and borehole water recorded TDS values of 12.55 mg/L and 17.65 mg/L respectively.

Measured pH values ranged from mildly acidic to near-neutral. Distilled water and borehole water both recorded a pH of 5.60. Sachet water had a pH of 6.00, while tap water recorded the highest pH at 6.60.

Calcium concentrations differed markedly between water sources. Tap water showed the highest calcium content at 60 mg/L. Borehole water recorded 8 mg/L, sachet water 6.4 mg/L and distilled water 2 mg/L. Magnesium was absent in distilled water, while tap water, sachet water and borehole water recorded magnesium concentrations of 10 mg/L, 2 mg/L and 6 mg/L respectively.

Chloride concentrations ranged from 12 to 40 mg/L. Distilled water recorded the highest chloride concentration at 40 mg/L, followed by tap water at 30 mg/L, borehole water at 28 mg/L and sachet water at 12 mg/L.

Water hardness, expressed as $CaCO_3$, reflected the combined calcium and magnesium content. Distilled water showed a hardness of 2 mg/L. Tap water recorded the highest hardness at 70 mg/L. Sachet water and borehole water recorded hardness values of 6 mg/L and 14 mg/L respectively.

Sodium concentrations ranged from 3.15 to 10.52 mg/L. Distilled water recorded the highest sodium concentration at 10.52 mg/L, followed by tap water at 7.89 mg/L. Borehole water and sachet water recorded sodium concentrations of 3.68 mg/L and 3.15 mg/L respectively. Potassium concentrations were low for all water types, ranging from 0.63 to 2.10 mg/L.

Discussion

General Performance Trends Across Water Types

Across all four water sources, PEM electrolyser performance differences were modest. Hydrogen production times differed by approximately 11%, SEC by about 8%, and average operating voltage by less than 1%. All water types supported stable hydrogen generation over repeated short-term tests without electrical instability or visible degradation.

From an energy conversion perspective, these results indicate that short-term PEM electrolyser performance is not governed solely by water purity, but rather by a balance between ionic transport properties and operating conditions. Manufacturer water-quality specifications are primarily designed to ensure long-term durability. Over short operating periods, the present results show that systems can tolerate a wider range of water chemistries while maintaining acceptable energy conversion efficiency.

Hydrogen Production Rate and Short-Term Conductivity Effects

Hydrogen production occurred fastest with tap water, followed by sachet water, borehole water and distilled water. This ordering aligns closely with the measured electrical conductivities of the water sources. Tap water exhibited a conductivity of 275 µS/cm, compared with 35.3 µS/cm for borehole water, 25.10 µS/cm for sachet water and only 4.55 µS/cm for distilled water.

Higher conductivity reduces ohmic resistance within the electrolysis cell and facilitates charge transport, leading to higher current at similar applied voltages. The near-identical operating voltages observed across water types indicate that improved hydrogen production rates for non-distilled water were achieved without additional electrochemical overpotential.

Energy Efficiency and SEC

While higher conductivity accelerated hydrogen production, it did not always improve energy efficiency. Borehole water achieved the lowest SEC (3.82 Wh/L), marginally outperforming distilled water, whereas sachet water showed the highest SEC (4.14 Wh/L).

Borehole water exhibited moderate conductivity (35.3 µS/cm) and TDS (17.65 mg/L), together with moderate hardness (14 mg/L as $CaCO_3$). This combination appears sufficient to enhance ionic transport without introducing the higher resistive or polarization effects associated with more heavily mineralised water. In contrast, sachet water showed lower hardness and lower divalent ion content, which may have limited its ability to support efficient proton transport despite faster hydrogen production than distilled water.

Borehole Water: Short-Term Advantages and Long-Term Considerations

Borehole water demonstrated favourable short-term performance, combining relatively fast hydrogen production with the lowest SEC among all tested sources. Its moderate concentrations of calcium (8 mg/L) and magnesium (6 mg/L) contributed to improved conductivity while avoiding the very high hardness observed for tap water.

However, this short-term advantage does not imply long-term compatibility. Mineral-containing waters are known to cause membrane ion exchange, scaling and catalyst degradation over extended operating periods. The absence of visible fouling in this study reflects the limited cumulative run time rather than guaranteed durability.

Sachet Water Performance and Treated Drinking Water Chemistry

Despite being widely perceived as purified drinking water, sachet water did not offer energy efficiency advantages. Its measured conductivity (25.10 µS/cm), low hardness (6 mg/L as $CaCO_3$) and low divalent cation content supported faster hydrogen production than distilled water but resulted in the highest SEC. This indicates that water treatment processes optimised for drinking quality do not necessarily yield ionic compositions favourable for electrochemical energy conversion.

Electrical Stability and Electrode Conditioning Effects

All water types exhibited a consistent test progression pattern in which the first cycle was faster than subsequent cycles. This behaviour was independent of water source and is therefore attributed to electrode conditioning effects rather than water chemistry.

Visual Inspection Versus Electrochemical Sensitivity

No visible electrode fouling or discoloration was observed for any water type. Nevertheless, measurable differences in SEC and production rate were evident. This demonstrates that water-quality effects manifest at the electrochemical scale well before macroscopic deposits become visible.

Implications for Intermittent and Off-Grid Hydrogen Systems

The findings are particularly relevant for off-grid and renewable-powered hydrogen systems, which often operate intermittently and accumulate limited daily run times. Under such conditions, short-term performance and energy efficiency are critical. The results indicate that municipal tap water and borehole water can support acceptable short-term PEM electrolyser operation without immediate efficiency penalties. Distilled water is not necessarily optimal, while sachet water offers no technical advantage despite its perceived purity.

Scope Limitations and Future Work

This study focused on short-term performance and did not assess long-term durability. Although water chemistry was characterised, extended cycling, membrane analysis and degradation studies are required to quantify lifetime effects. Results presented here provide a screening basis for identifying water sources suitable for such extended investigations.

Conclusions and Recommendations

This work used systematic comparative tests of a PEM electrolyser supplied with four commonly available water sources—distilled water, municipal tap water, sachet water and borehole water—to address four main objectives. The following conclusions are drawn:

- All four water sources produced hydrogen successfully, with only modest performance differences. Hydrogen production time varied by approximately 11% and SEC by about 8%. Distilled water did not perform best. Non-distilled water sources produced hydrogen 7–11% faster, and borehole water delivered the lowest SEC. These findings demonstrate that short-term PEM electrolyser operation is feasible using locally available water sources that fall outside typical manufacturer purity specifications, provided operation is intermittent and performance is monitored.
- SEC was highly reproducible and proved more reliable than production time as a metric for comparing water quality effects. Borehole water consistently gave the lowest SEC, while sachet water was the least energy efficient. All test series exhibited a fresh-electrode effect, indicating that experimental protocols and operational monitoring should account for electrode conditioning when comparing performance across water sources.
- Electrodes appeared visually identical for all water types despite measurable performance differences. This confirms that water quality effects manifest at microscopic and electrochemical scales before visible deposits form. Consequently, monitoring operating voltage and SEC provides a more sensitive indication of water-related performance changes than visual inspection alone.

For Applications with Daily Run Times of Approximately 4–6 hours:

- Municipal tap water and borehole water can provide acceptable short-term PEM electrolyser performance.
- Sachet water offers no technical advantage despite its purification and higher cost.
- Water treatment decisions should be based on a comparison of treatment cost, expected operating hours and maintenance effort, rather than a blanket assumption that ultra-pure water is always required.
- Systems operating with non-ideal water should incorporate simple performance monitoring, with particular emphasis on voltage and SEC trends.

This study focused exclusively on short-term operation and therefore cannot predict long-term durability, which will depend on cumulative operating hours, extended cycling and membrane–electrode interactions. While physicochemical properties of the water sources were measured to support interpretation of short-term performance trends, extended durability testing and ageing studies are required to quantify long-term degradation mechanisms and maintenance requirements.

Even with these constraints, the findings help to lower perceived barriers to PEM electrolyser deployment in resource-limited contexts. They show that non-ideal but locally available water sources merit systematic investigation rather than automatic rejection, and that for short or intermittent operation, the relationship between water quality and energy performance is more nuanced than is often assumed. Progress towards long-term deployment will require further work on durability, maintenance strategies, water chemistry evolution and techno-economic trade-offs to support robust system design and investment decisions.

Data Availability

The datasets generated and analysed during the current study are not publicly available. They can be obtained from the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Emmanuel Akono Sarsah: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration.

Abdul-Rahim Bawa: Formal analysis, Writing – review & editing, Resources, Validation.

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