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Evaluation of electrolyte effectiveness in HHO gas production: A systematic analysis of KOH, NaOH and $NaHCO_3$ concentrations

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ABSTRACT

The effectiveness of different electrolytes in HHO gas production during electrolysis is not well understood, which complicates the selection of the most efficient electrolyte. This study aimed to systematically evaluate and compare the performance of common electrolytes (KOH, NaOH and $NaHCO_3$) to identify the most efficient one. The study evaluated the effectiveness of KOH, NaOH, and $NaHCO_3$ as electrolytes for HHO gas production during electrolysis. Using the STWEG-M1 Oxyhydrogen Gas Generator, gas output was measured at concentrations from 0.0125 M to 0.250 M via water displacement. ANOVA revealed significant differences ($p < 0.05$), with KOH yielding the highest gas volume (245.7 mL at 0.250 M), followed by NaOH (180.6 mL), while $NaHCO_3$ was least effective (20.0 mL). Results confirmed that increasing electrolyte concentration enhanced electrolysis efficiency by improving ion availability and charge transport, highlighting the importance of electrolyte selection in optimising performance.

1. Introduction

The global reliance on hydrocarbon-based fuels, which account for approximately 85% of global energy production, underscores their critical role in energy generation, industrial production, and transportation [1]. However, the combustion of these fossil fuels leads to significant environmental degradation, contributing to greenhouse gas emissions and air pollution, which in turn cause various health issues [2]. In contrast, HHO gas, produced through water electrolysis, offers a promising alternative due to its renewable, recyclable, and non-polluting properties [3]. This makes it an attractive option for mitigating environmental impact while fulfilling energy demands. Recent advancements in electrolysis technology have further highlighted the potential of HHO gas as an efficient and sustainable energy source [4].

The optimisation of HHO gas production has garnered significant attention due to its potential as a green fuel. Masjuki et al. [3] highlighted the importance of optimising HHO gas production, citing its wide range of applications and environmental advantages. Catalysts are crucial in enhancing the efficiency of electrolysis by lowering the activation energy required for the dissociation of water molecules [2]. Hydrogen fuel cell technology, which relies on the electrochemical reaction between hydrogen and oxygen to generate electricity, represents a promising avenue for sustainable energy production, though it is

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distinct from the electrolysis process used to generate HHO gas [5]. Hydrogen fuel cells have been in use since the nineteenth century and offer a cleaner and more efficient alternative to traditional energy sources [6,7]. Recent studies by Zhang et al. [8] and Ahmed et al. [9] have demonstrated that modifying catalyst composition can significantly enhance the efficiency of HHO gas production, further justifying the need for systematic research in this area. Key to improving the electrolysis process for HHO gas production is understanding the role of electrolytes and electrode materials, both of which influence the efficiency and overall performance of the process [10,11]. Catalysts are especially important in improving the rate of water decomposition, thus enhancing gas production efficiency [5,12].

Hydroxy gas, or HHO gas, was first developed by Williams A. Rhodes as a magnetically bonded combination of 2 mol of hydrogen and 1 mol of oxygen, with his multi-cell oxyhydrogen generator patented on July 26, 1966 [13,14]. This was followed by Yull Brown's research into using HHO gas in internal combustion engines, leading to the coining of the term "Brown's gas" and his patent granted on 29 March 1977 [15,16]. Despite initial scepticism surrounding the practical use of HHO gas, ongoing research continues to explore its potential. Puha Rich's study, for example, provided valuable insights into the energy required to break water molecules and the energy released during the combustion reaction [17]. Theories surrounding Brown's gas suggest unique properties, such as electromagnetic field shifts during its transformation [18], while Viktor Schauberger's work introduced innovative ideas regarding energy generation through energy vortexes [19]. Recent research by Wang et al. [20], has further supported the potential of HHO gas in reducing carbon emissions when used as a supplementary fuel in internal combustion engines.

Hydroxy gas has several unique properties, notably its ability to exist in a monoatomic form within a container and exhibit explosive characteristics with a higher energy potential than diatomic flames [18]. This high specific energy per unit weight positions HHO gas as a promising alternative fuel source [21]. The development of HHO gas kits has greatly improved the efficiency of gas production [22]. Catalysts play a crucial role in accelerating the electrolysis process by lowering activation energy, with alkaline or acidic solutions enhancing conductivity but possibly introducing impurities into the system [5,23]. The resistance of materials involved in electrolysis affects both electron and ion flow, and optimising electrode spacing can improve efficiency by reducing resistance [23]. Additionally, temperature influences the rate of reaction and energy consumption, with higher temperatures increasing ion mobility and improving reaction efficiency [24]. Pressure, on the other hand, affects energy usage and the ohmic resistivity of the electrolyte, which in turn influences gas bubble behaviour during electrolysis [25]. Proper electrode alignment and spacing further enhance the efficiency of the electrolytic process [2,26]. Recent findings by Patel [27] indicate that microstructural modifications in electrode materials can further optimise the efficiency of HHO gas production.

Operating conditions such as temperature, pressure, and current have a substantial impact on the performance of HHO gas production. Increasing the temperature accelerates ion mobility within the electrolyte, reducing resistance and allowing for more efficient water dissociation into hydrogen and oxygen gases. However, excessive temperatures can damage the electrolyte and other system components, which may reduce the overall sustainability and efficiency of the process. Pressure is another important operating condition, influencing both the energy required for electrolysis and the resistivity of the electrolyte. While increased pressure can enhance gas production by improving bubble formation and detachment from electrodes, it may also raise energy consumption and increase resistivity, making it crucial to optimise pressure settings for maximum efficiency. According to a study by Chang et al. [28], an optimal balance between pressure and temperature is necessary to achieve peak HHO gas production efficiency without compromising system durability.

The alignment and spacing of electrodes play a key role in optimising HHO gas production. If electrodes are placed too closely together, excessive heat may accumulate, leading to inefficiencies and possible damage to the system. On the other hand, too much distance between electrodes can hinder the flow of current, reducing gas production rates. Research has shown that maintaining optimal electrode spacing and alignment can greatly improve the electrolysis process, minimising energy losses and promoting uniform gas production, which enhances overall system performance. Recently, Gohar and Hassan [29] have explored innovative electrode designs that further enhance the efficiency of electrolysis systems for HHO gas production.

In addition to these operating conditions, the type of electrolyte used has a significant effect on HHO gas production. Electrolytes such as potassium hydroxide (KOH), sodium hydroxide (NaOH), and sodium bicarbonate ($NaHCO_3$) are commonly used in electrolysis due to their distinct properties that affect conductivity. Alkaline electrolytes like KOH and NaOH are particularly effective because they offer high ionic conductivity, facilitating the flow of electricity and improving the electrolysis process. These electrolytes lower the energy barrier for water dissociation, thereby enhancing gas production efficiency. Sodium bicarbonate, while less effective, is still used in certain applications due to its lower corrosiveness compared to KOH and NaOH. Furthermore, the concentration of the electrolyte is a crucial factor—higher concentrations generally improve conductivity, but excessive concentrations can lead to issues such as scaling or contamination, which may negatively affect the electrolysis process. Recent experimental work by El Kady et al. [30], has identified optimal concentration ranges for KOH and NaOH, reducing inefficiencies and improving overall gas yield.

The influence of operating conditions such as temperature, pressure, current, and electrode spacing on HHO gas production has been well-documented in studies by Sudrajat et al. [5] and Göllei [31]. Santilli's research on oxyhydrogen gas as "magnecules" has further highlighted the unique properties and potential environmental benefits of HHO gas [18]. Despite the growing interest in HHO gas as a supplementary fuel, there remains a gap in the literature concerning the optimisation of the production process, particularly in terms of catalyst selection. Subramanian & Ismail [10] identified key parameters for HHO production, emphasising the need for optimisation. A recent meta-analysis by **Chen et al.,** [32] has consolidated previous findings, highlighting critical gaps in current research and the need for improved standardisation in electrolysis studies.

The effectiveness of different electrolytes in HHO gas production remains inadequately understood, with limited research on their optimal selection and concentration. While previous studies have examined the effects of operating conditions such as temperature and pressure, a systematic comparison of commonly used electrolytes—KOH, NaOH, and $NaHCO_3$—under controlled conditions is lacking. By employing a controlled experimental approach with the STWEG-M1 Oxyhydrogen gas generator and rigorous statistical analysis, the research establishes the most effective electrolyte. The findings provide quantitative evidence to resolve uncertainties in electrolyte selection, improving electrolysis efficiency and guide practical applications.

2. Materials and methods

2.1. Materials

The reagents used in this study were of analytical grade, including 99% sodium bicarbonate ($NaHCO_3$), 97% sodium hydroxide (NaOH), and 85% potassium hydroxide (KOH). Various laboratory glasswares were utilized to ensure precise measurements, including 100 ml, 250 ml, 350 ml, and 500 ml glass measuring cylinders, 500 ml and 1 L volumetric flasks, 200 ml beakers, and 500 ml conical flasks. Additional materials included a spatula for handling solid reagents, aluminum foil for covering solutions, deionized water as the solvent, 4 L amber bottles for storing prepared electrolyte solutions, a wash bottle for controlled

dispensing of deionized water, and a dropper for adding small quantities of solutions.

2.2. Equipment

The STWEG-M1 Oxyhydrogen Gas Generator (Fig. 1) is a specialised electrolysis system designed for efficient HHO gas production. It features twelve electrolyser cells in series, which are responsible for splitting water molecules into hydrogen and oxygen gases. Each cell receives approximately 1.02 V and has an active electrode area of 136.85 cm^2, while the 13.2 cm diameter plates, made from 316L stainless steel, ensure durability and corrosion resistance. The unit is enclosed in a sturdy acrylic case, which provides structural stability while allowing visual monitoring of the electrolysis process.

To power the system, the STWEG-M1 is equipped with a 460W power source and electrical power cables, delivering the necessary energy for efficient electrolysis. It includes a self-adaptive adaptor that converts 110V or 220V electricity into a 12.2V working voltage, ensuring stable operation. The generated HHO gas passes through a rubber tube, which facilitates the movement of moist HHO gas from the electrolyser. To enhance gas purity, the system incorporates an acrylic bubbler, which effectively removes impurities before the gas is channelled through a rubber tube for the passage of dry HHO gas. Finally, the purified gas is directed to a gas torch, which can be used for combustion applications.

To support operational accuracy and stability, additional equipment includes an analytical balance for precise electrolyte measurements, a water bath with a 20-litre capacity to maintain consistent temperature, a stopwatch for precise time control, and a shaker to ensure homogeneity in prepared solutions. The dry-cell design of the STWEG-M1 minimises heat generation, improving energy efficiency and maintaining stable hydrogen production. These features collectively make the STWEG-M1 an optimal system for controlled and efficient HHO gas generation.

2.3. Experimental methodology for HHO gas production, measurement and data analysis

The experiment was conducted using the STWEG-M1 Oxyhydrogen Gas Generator to produce HHO gas under controlled conditions. A systematic measurement setup was implemented to quantify the volume of gas produced. The setup included a water bath filled with approximately 18 L of deionized water and a 500 ml glass measuring cylinder, which was completely filled with deionized water and inverted. The bubbler of the STWEG-M1 apparatus contained 250 ml of deionized water to regulate the gas flow, ensuring accurate volume measurement.

Electrolyte solutions were prepared at seven different molar concentrations: 0.0125 M, 0.025 M, 0.05 M, 0.10 M, 0.15 M, 0.20 M, and 0.25 M. The experimental procedure commenced by rinsing the STWEG-M1 unit with 0.0125 M $NaHCO_3$ electrolyte solution and filling the generator with 350 ml of the same solution, occupying approximately three-quarters of the apparatus. The generator was activated for 30 s to initiate HHO gas production before connecting the bubbler outlet to the inverted 500 ml measuring cylinder. Gas volume was measured using the downward water displacement method over a 10-s period, and seven consecutive readings were recorded to ensure precision and repeatability [33,34].

Following each measurement, the STWEG-M1 generator and bubbler were thoroughly rinsed with deionized water to eliminate any residual electrolyte. The process was then repeated for increasing concentrations of $NaHCO_3$ electrolyte. After completing the $NaHCO_3$ trials, the experiment was replicated with NaOH and KOH electrolytes to facilitate a comparative analysis of gas production efficiency.

The STWEG-M1 Oxyhydrogen Gas Generator functions based on the principle of water electrolysis, where an electric current dissociates water molecules into hydrogen (H_2) and oxygen (O_2) gases. The half-reactions occurring at the electrodes are as follows:

$$\text{Cathode half} - \text{reaction}: 4H^{+}_{(aq)} + 4e^{-} \rightarrow 2H_{2(g)}$$

$$\text{Anode half} - \text{reaction}: 4OH^{-}_{(aq)} \rightarrow O_{2(g)} + 2H_2O_{(aq)} + 4e^{-}$$

$$\text{HHO synthesis}: 2H_{2(g)} + O_{2(g)} \rightarrow 2HHO_{(g)}$$

The data obtained from the gas volume measurements were statistically analysed using Genstat V.12 software. A one-way Analysis of Variance (ANOVA) was performed to assess the effect of electrolyte type and concentration on HHO gas production. Statistical significance was determined based on a threshold p-value of less than 0.05. Tukey's Honest Significant Difference (HSD) test was applied for mean separation, facilitating pairwise comparisons between electrolyte concentrations to control Type I errors and identify significant differences in gas production rates. This approach ensured robust statistical interpretation and provided reliable insights into the optimal electrolyte selection and concentration for maximising HHO gas output.

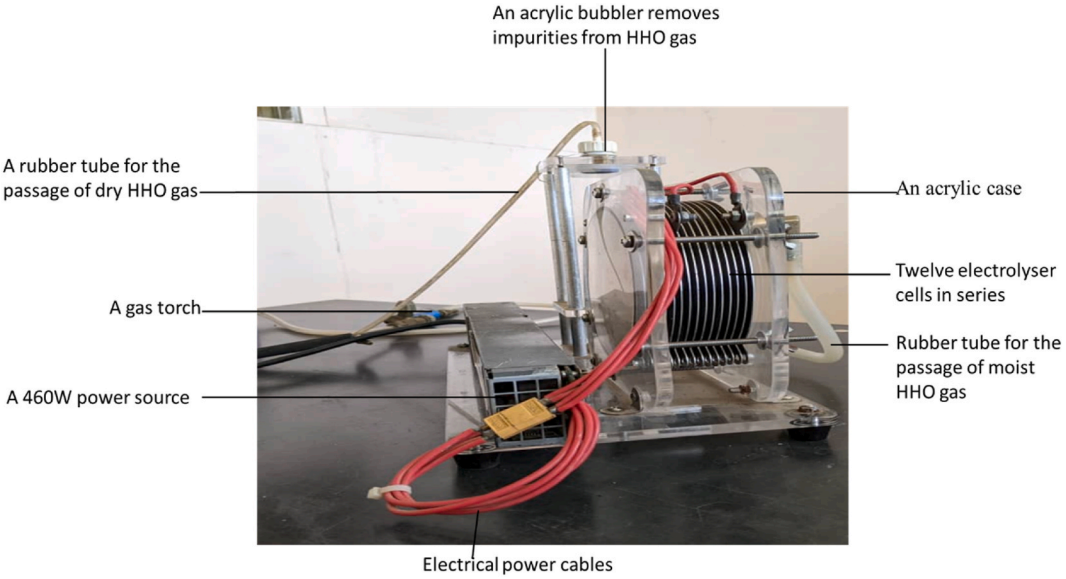

Fig. 1. The STWEG-M1 oxyhydrogen gas generator.

3. Results and discussion

3.1. Analysis of HHO gas production from KOH electrolyte solutions

The results presented in Table 1 illustrate the influence of KOH electrolyte concentration on HHO gas production, demonstrating a direct correlation between electrolyte molarity and gas yield. At lower concentrations of 0.0125 M and 0.025 M, no measurable gas production was observed, indicating that these concentrations were below the threshold required to initiate significant electrolysis. However, at 0.05 M, gas production commenced, with a mean HHO gas volume of 62 mL, highlighting the minimum concentration necessary to sustain electrolysis. As the concentration increased, gas production improved significantly, reaching 112 mL at 0.1 M, 154 mL at 0.15 M, and 244 mL at 0.25 M, with each increment showing statistical significance ($p < 0.01$). These findings align with trends reported by Coats and Richardson [34] who observed that increasing electrolyte concentration enhances the ionic conductivity of the solution, thereby reducing internal resistance and improving electrolysis efficiency.

Similarly, the analysis of NaOH electrolytes followed a comparable trend of KOH, although with slightly lower gas production at each concentration level. At the lowest concentrations of 0.0125 M and 0.025 M, no gas was produced, mirroring the results for KOH. At 0.05 M, a mean gas volume of 30.86 mL was observed ($F = 18.00$, $p < 0.05$), while at 0.1 M, the mean volume increased to 64.29 mL ($F = 42.86$, $p < 0.01$). At higher concentrations, the gas production stabilised: at 0.15 M, the mean volume was 120 mL ($F = 166.00$, $p < 0.01$), and at 0.25 M, the mean volume was 180.43 mL ($F = 485.00$, $p < 0.01$).

The observed trends for both electrolytes suggest that increasing the concentration of the electrolyte solution enhances the efficiency of HHO gas production. At higher concentrations (0.15 M and above), the gas production stabilised, with minimal fluctuation between individual measurements. This stability indicates that, at these concentrations, the system reaches an optimal operational range where the electrolysis process operates at maximum efficiency, and further increases in concentration result in diminishing returns in terms of additional gas production. Notably, this trend is consistent with previous findings that higher electrolyte concentrations generally lead to more efficient electrolysis by increasing ion availability, which in turn enhances the rate of HHO gas production [35,36].

3.2. Analysis of HHO gas production from NaOH electrolyte solutions

The analysis of HHO gas production from $NaHCO_3$ (sodium bicarbonate) electrolyte solutions reveals a markedly different trend compared to KOH and NaOH electrolytes. Table 3 presents gas production at varying $NaHCO_3$ concentrations, from 0.0125 M to 0.25 M. At the lowest concentrations of 0.0125 M, 0.025 M, as well as 0.050 M and 0.100 M, the mean gas production was 0 mL, with $F = 0.00$ and $p = 1.00$. This indicates that these concentrations are insufficient to support the electrolysis process, likely due to $NaHCO_3$'s lower ion conductivity compared to stronger electrolytes like KOH and NaOH. The lack of measurable gas production highlights the inefficacy of $NaHCO_3$ at these lower concentrations. At 0.150 M, HHO gas production begins, though at a minimal level. The mean gas volume at this concentration was 4.7 mL, with individual values ranging from 3 mL to 5 mL ($F = 4.29$, $p = 0.08$). While this represents a slight increase in gas production compared to the zero-production levels at lower concentrations, the rise is not statistically significant at the 0.05 level, suggesting that $NaHCO_3$ begins to influence the electrolysis process at this concentration, but its impact remains limited. At 0.200 M, the mean gas volume increased slightly to 5.0 mL, with values ranging from 3 mL to 6 mL ($F = 7.00$, $p = 0.05$). This modest increase in gas production indicates some improvement in the electrolysis process, though the variation across trials suggests that the benefits of using $NaHCO_3$ at this concentration remain statistically weak. The highest concentration of 0.250 M achieved a mean gas volume of 20.0 mL, with values ranging from 18 mL to 26 mL ($F = 51.67$, $p < 0.01$). This significant increase in gas production demonstrates that $NaHCO_3$ becomes notably more effective at higher concentrations. However, even at this highest level, $NaHCO_3$ remains less efficient than KOH or NaOH at equivalent concentrations.

Table 1
KOH electrolyte.

Electrolyte	Mean Volume of HHO Gas (mL)							Mean
Conc. (M)	V1	V2	V3	V4	V5	V6	V7	(mL)
0.0125	0	0	0	0	0	0	0	0
0.025	0	0	0	0	0	0	0	0
0.05	62	62	64	62	64	64	58	62
0.1	112	112	113	112	113	120	104	112
0.15	150	152	152	158	154	150	160	154
0.2	172	172	172	164	160	172	172	169
0.25	250	250	260	260	210	250	230	244

Table 2
NaOH electrolyte.

Electrolyte	Mean Volume of HHO Gas (mL)							Mean
Conc. (M)	V1	V2	V3	V4	V5	V6	V7	(mL)
0.0125	0	0	0	0	0	0	0	0
0.025	0	0	0	0	0	0	0	0
0.05	32	32	31	32	24	24	28	30.86
0.1	62	60	60	62	68	70	72	64.29
0.15	120	120	121	124	121	118	116	120
0.2	141	139	140	141	140	128	132	137.14
0.25	181	182	182	174	182	178	174	180.43

Table 3
$NaHCO_3$ electrolyte.

Electrolyte	Mean Volume of HHO Gas (mL)							Mean
Conc. (M)	V1	V2	V3	V4	V5	V6	V7	(mL)
0.025	0	0	0	0	0	0	0	0
0.05	0	0	0	0	0	0	0	0
0.1	0	0	0	0	0	0	0	0
0.15	5	5	3	5	5	3	5	4.86
0.2	5	5	6	5	3	6	3	4.86
0.25	18	20	20	26	18	20	24	20.86

3.3. Analysis of HHO gas production from $NaHCO_3$ electrolyte solutions

The relatively low gas production from $NaHCO_3$ at concentrations below 0.250 M indicates that it is less efficient as an electrolyte for HHO gas generation compared to NaOH and KOH. $NaHCO_3$'s lower ion conductivity likely reduces its ability to facilitate the electrolysis process, resulting in reduced gas production and lower energy efficiency. Even at 0.250 M, where the mean gas volume reached 20.0 mL, the volume remains significantly lower than that produced by KOH and NaOH at the same concentration.

It was further observed that KOH was a more effective electrolyte than NaOH and $NaHCO_3$ yielding higher gas production at equivalent molarities due to its superior ionic mobility. In terms of energy density of KOH, NaOH and $NaHCO_3$, KOH had more energy density than NaOH and $NaHCO_3$ because the increased ion availability leads to more effective dissociation of water molecules into hydrogen and oxygen, thereby maximising the output gas volume for the same amount of input energy.

A comparison between $NaHCO_3$, KOH, and NaOH shows stark differences in gas production and efficiency. KOH and NaOH consistently produced significantly more HHO gas at all tested concentrations, particularly from 0.100 M and above, where $NaHCO_3$ produced little to

no measurable gas. This discrepancy is likely due to the superior ion conductivity of KOH and NaOH, which supports a more effective electrolysis process. At 0.250 M, $NaHCO_3$ produced a mean gas volume of 20.0 mL, still far below the volumes generated by KOH and NaOH at the same concentration. This result highlights the relative inefficiency of $NaHCO_3$ as an electrolyte, demonstrating that while it can be used for HHO gas production, it is not as energy-efficient or effective as KOH and NaOH.

The comparative analysis of HHO gas production across different electrolytes—KOH, NaOH, and $NaHCO_3$—demonstrates significant differences in their effectiveness at various concentrations (Table 4). KOH proved to be the most efficient electrolyte for HHO gas production at all tested concentrations. The gas production began to increase notably at 0.05 M, where the mean volume recorded was 62.4 ± 2.3 mL. Statistical analysis yielded a highly significant F-statistic of 75, with a p-value of less than 0.01, indicating that KOH significantly enhances the water splitting activity at this concentration. At 0.1 M, gas production rose to 113.0 ± 4.9 mL, and the highest volume observed was at 0.25 M, with a mean volume of 245.7 ± 17.6 mL ($F = 1034$, $p < 0.01$). These]findings confirm that KOH is an exceptionally efficient electrolyte, significantly improving gas production with increasing concentration. The observed correlation between electrolyte concentration and enhanced gas production suggests that KOH increases ion conductivity and energy conversion efficiency in the electrolysis process [34].

NaOH, while following a similar trend to KOH, showed slightly lower gas production at comparable concentrations. At 0.05 M, the mean gas volume was 29.0 ± 3.1 mL ($F = 18$, $p < 0.05$), significantly lower than that of KOH at the same concentration. However, gas production increased progressively with concentration, reaching 65.7 ± 4.7 mL at 0.1 M and 180.6 ± 4.3 mL at 0.25 M ($F = 485$, $p < 0.01$). Although NaOH is still an effective electrolyte, its performance is not as strong as KOH, particularly in terms of overall gas production. This indicates that while NaOH's efficiency is considerable, its energy density and ion conductivity are slightly inferior to those of KOH, rendering it a less potent electrolyte for the water splitting activity as corroborated by Ref. [35].

$NaHCO_3$, in contrast, exhibited the lowest efficiency in HHO gas production across all concentrations tested. No measurable gas was produced at concentrations below 0.15 M, and at 0.15 M, the mean gas volume was only 4.4 ± 0.8 mL ($F = 4.29$, $p = 0.08$), indicating minimal gas production. A slight increase was observed at 0.2 M, with a mean gas volume of 4.7 ± 1.3 mL ($F = 7$, $p = 0.05$), but this remained negligible when compared to KOH and NaOH. Only at 0.25 M did $NaHCO_3$ show a more substantial increase in gas production, achieving a mean volume of 21.0 ± 3.5 mL ($F = 51.67$, $p < 0.01$). However, even at this concentration, $NaHCO_3$ produced significantly less gas than KOH or NaOH at comparable concentrations. These results suggest that $NaHCO_3$ is far less effective as an electrolyte for HHO gas production, likely due to its reduced ion conductivity. Even at higher concentrations, $NaHCO_3$'s energy density and overall efficiency in facilitating the water splitting activity remain inferior to those of KOH and NaOH as supported by Ref. [27].

Table 4
Overall means of HHO gas produced for KOH, NaOH and $NaHCO_3$ electrolytes.

Electrolyte	Concentration (M)	Overall Mean Volume (mL) of HHO Gas Produced After 10 s	F-Statistic	p-Value
KOH	0.0125	0.0 ± 0.0	0	1
	0.025	0.0 ± 0.0	0	1
	0.05	62.4 ± 2.3	75	<0.01
	0.1	113.0 ± 4.9	210	<0.01
	0.15	154.6 ± 3.8	392	<0.01
	0.2	168.0 ± 5.2	526	<0.01
	0.25	245.7 ± 17.6	1034	<0.01
NaOH	0.0125	0.0 ± 0.0	0	1
	0.025	0.0 ± 0.0	0	1
	0.05	29.0 ± 3.1	18	<0.05
	0.1	65.7 ± 4.7	42.86	<0.01
	0.15	119.7 ± 2.1	166	<0.01
	0.2	140.0 ± 4.4	225	<0.01
	0.25	180.6 ± 4.3	485	<0.01
$NaHCO_3$	0.0125	0.0 ± 0.0	0	1
	0.025	0.0 ± 0.0	0	1
	0.05	0.0 ± 0.0	0	1
	0.1	0.0 ± 0.0	0	1
	0.15	4.4 ± 0.8	4.29	0.08
	0.2	4.7 ± 1.3	7	0.05
	0.25	21.0 ± 3.5	51.67	<0.01

3.4. Comparative analysis of HHO gas production from KOH, NaOH, and $NaHCO_3$ electrolytes

The variations in the performance of KOH, NaOH, and $NaHCO_3$ can be ascribed to their distinct chemical properties, particularly their ion conductivity. Among these electrolytes, KOH exhibited the highest ion conductivity, resulting in superior efficiency and the greatest HHO gas production, even at lower concentrations. NaOH, while still effective, generated comparatively lower volumes of gas and exhibited a reduced energy density, indicating a slightly lower ion conductivity than KOH. Conversely, $NaHCO_3$ displayed poor performance across all concentrations, which can be attributed to its limited ion dissociation and lower conductivity, thereby impeding its ability to enhance water splitting activity. The statistical analysis further supports these observations, with KOH demonstrating highly significant results at concentrations exceeding 0.05 M, while NaOH exhibited strong significance at 0.25 M. In contrast, $NaHCO_3$ achieved only marginal significance at 0.25 M, reinforcing its limited efficacy as an electrolyte for HHO gas production [36,37].

Energy density, which refers to the efficiency of converting electrical energy into chemical energy stored in the produced gas, was found to be highest for KOH and lowest for $NaHCO_3$. The greater gas yields obtained with KOH and NaOH at each concentration level suggest a more effective electrolysis process, ensuring enhanced energy conversion. By contrast, the lower gas volumes observed with $NaHCO_3$ indicate a less efficient process, likely stemming from its reduced ion mobility and conductivity. This renders $NaHCO_3$ unsuitable for applications requiring high energy efficiency. These findings highlight the critical role of electrolyte selection in optimising electrolysis performance, with KOH and NaOH emerging as the more effective choices for facilitating water splitting activity [38,39].

A general increase in electrolyte concentration enhances gas production during electrolysis by improving ion availability, increasing conductivity, and raising the energy density of the output gas. Electrolytes such as KOH, NaOH, and $NaHCO_3$ exhibit greater ion dissociation at elevated concentrations, thereby promoting efficient electrolysis through the reduction of charge transfer resistance [36]. An increase in the number of charge carriers at higher concentrations enhances conductivity while simultaneously lowering the voltage required to sustain water splitting activity [28]. Although excessive concentrations may reduce ion mobility due to intensified ion-ion interactions, the overall increase in available ions compensates for this effect, thereby sustaining effective charge transport [38]. Enhanced conductivity facilitates more efficient electron transfer, reducing energy losses and accelerating the evolution of hydrogen and oxygen gases [37]. This increase in gas production directly impacts the energy density of the output gas, as higher hydrogen and oxygen yields at a given energy input result in greater stored energy per unit volume [39].

When comparing NaOH with KOH, it was evident that NaOH yielded marginally lower volumes of HHO gas at equivalent concentrations. This discrepancy can be attributed to the intrinsic chemical differences between NaOH and KOH, particularly their ion conductivity. Nonetheless, the positive correlation between electrolyte concentration and gas

production efficiency remained consistent for both electrolytes, reinforcing the conclusion that increased concentration enhances electrolysis efficiency and energy density. Although KOH consistently produced higher gas volumes at all concentration levels, the trend of improved performance with increasing concentrations was observed in both electrolytes. The statistical evaluation of HHO gas production using NaOH, summarised in Table 2, confirmed the significance of these findings. The F-statistics and p-values provided compelling evidence that higher electrolyte concentrations significantly improve gas output, with values of $F = 18.00$ ($p < 0.05$) at 0.050 M, $F = 42.86$ ($p < 0.01$) at 0.100 M, $F = 166.00$ ($p < 0.01$) at 0.150 M, $F = 225.00$ ($p < 0.01$) at 0.200 M, and $F = 485.00$ ($p < 0.01$) at 0.250 M. These results underscore the substantial impact of increased electrolyte concentrations on electrolysis efficiency.

The findings of this study are in accordance with theoretical predictions and existing literature, which suggest that higher electrolyte concentrations improve electrolysis efficiency and gas production [27, 40]. Further validation is provided by studies emphasising the necessity of optimising electrolyte concentrations to maximise electrolysis performance [41]. The experimental data confirm that NaOH is an effective electrolyte for electrolysis enhancement, with concentrations exceeding 0.150 M yielding the highest efficiency. Future research should focus on determining the precise optimal concentration levels for NaOH while investigating the underlying mechanisms responsible for these improvements in gas production.

4. Conclusion

KOH was the most efficient electrolyte for HHO gas production at the same volume and concentration, delivering the highest gas volumes due to its superior ionic conductivity and energy density. It consistently outperformed NaOH and $NaHCO_3$ across all concentrations, particularly from 0.100 M and above. At 0.250 M, KOH produced the highest gas yield (245.7 mL), while NaOH generated a slightly lower volume (180.6 mL). In contrast, $NaHCO_3$ exhibited poor performance, producing only 21.0 mL at 0.250 M and no measurable gas below 0.15 M due to its lower ion conductivity. Statistical analysis confirmed that increasing electrolyte concentration significantly improved electrolysis efficiency by enhancing ion availability and charge transport. Although higher concentrations slightly reduced ion mobility, the overall increase in charge carriers maintained effective conductivity and energy conversion, reinforcing the role of electrolyte selection in optimising electrolysis performance.

CRediT authorship contribution statement

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Declaration of competing 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.

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References

[1] Rolo I, Costa VA, Brito FP. Hydrogen-based energy systems: current technology development status, opportunities, and challenges. Energies 2023;17(1):180. https://doi.org/10.3390/en170100180.
[2] Essuman E, Kofi KO, Boateng FK. Performance evaluation of potassium hydroxide and sodium hydroxide electrolytes in oxyhydrogen fuel cells. J Energy Resour Technol 2019;141(7):072302. https://doi.org/10.1115/1.4042788.
[3] Masjuki HH, Ruhul AM, Mustafi NN, Kalam MA, Arbab MI, Fattah IR. Study of production optimization and effect of hydroxyl gas on a CI engine performance and emission fueled with biodiesel blends. Int J Hydrogen Energy 2016;41(33):14519–28. https://doi.org/10.1016/j.ijhydene.2016.05.149.
[4] Aghahosseini A, Bogdanov D, Breyer C. Towards sustainable energy systems: a comprehensive review of renewable hydrogen potential and deployment. Renew Sustain Energy Rev 2020;136:110322.
[5] Sudrajat A, Handayani EM, Tamaldin N, Yamin AKM. Principle of generator HHO hybrid multistack type production technologies to increase HHO gas volume. SHS Web Conf. 2018;49:02016. https://doi.org/10.1051/shsconf/20184902016.
[6] Nabil T, Dawood MMK. Theoretical investigation of fuel cell producing 1000 W power. American Journal of Modern Energy 2020;6:124–9. https://doi.org/10.11648/j.ajme.20200603.12.
[7] Chen X, Zhang Y, Xu S, Dong F. Bibliometric analysis for research trends and hotspots in heat and mass transfer and its management of proton exchange membrane fuel cells. Appl Energy 2023;333:120611. https://doi.org/10.1016/j.apenergy.2023.120611.
[8] Garagounis I, Vourliotis P, Stoukides M, Kyriakou V. Electrolysis for energy applications: current trends and future prospects. J Power Sources 2021;506:230065.
[9] Lee JS, Tai CH, Chen HM. Advances in alkaline electrolysis for hydrogen production: an overview of catalyst development. Int J Hydrogen Energy 2022;47(10):5886–902.
[10] Subramanian B, Ismail S. Production and use of HHO gas in IC engines. Int J Hydrogen Energy 2018;43(14):7140–54. https://doi.org/10.1016/j.ijhydene.2018.02.138.
[11] Koponen, J. **(2015).** *Review of water electrolysis technologies and design of renewable hydrogen production systems* (Master's thesis, Lappeenranta University of Technology, LUT School of Energy Systems). Retrieved from https://lutpub.lut.fi/bitstream/handle/10024/104326/MScThesis_JKK.pdf.
[12] Peng W, Wei J. Effects of electrolyte concentration on ionic conductivity and gas production in water electrolysis. J Power Sources 2020;448:227334. https://doi.org/10.1016/j.jpowsour.2019.227334.
[13] Ruoho S, Arkkio A. Partial demagnetization of permanent magnets in electrical machines caused by an inclined field. IEEE Trans Magn 2008;44(7):1773–8. https://doi.org/10.1109/TMAG.2008.923158.
[14] Vinayak S, Prakash C, Yadav AK, Singh VK, Mukhopadhyay S, Dixit A. High efficiency zero carbon emission oxy-hydrogen (HHO) generator. In: National conference on energy materials and devices. Singapore: Springer Nature Singapore; 2022. p. 299–310.
[15] Essuman SPK, Nyamful A, Yao V, Agbodemegbe SKD. Design and development of an oxyhydrogen generator for the production of Brown's (HHO) gas as a renewable source of fuel for the automobile industry. International Journal of Engineering Science Invention 2018;8:1–7.
[16] Bhardwaj S, Jayant A, Lohia V, Kaushik PM. An experimental investigation on the use of Brown gas in internal combustion engine. Journal of Energy Technology Policy 2018;5(4). https://doi.org/10.5897/JETP2018.0235. 2225–0573.
[17] Paparao J, Murugan S. Oxy-hydrogen gas as an alternative fuel for heat and power generation applications—a review. Int J Hydrogen Energy 2021;46(76):37705–35. https://doi.org/10.1016/j.ijhydene.2021.07.126.
[18] Brown MR. Experimental studies of magnetic reconnection. Phys Plasmas 1999;6(5):1717–24. https://doi.org/10.1063/1.873155.
[19] Rostami AB, Armandei M. Renewable energy harvesting by vortex-induced motions: review and benchmarking of technologies. Renew Sustain Energy Rev 2017;70:193–214. https://doi.org/10.1016/j.rser.2016.11.236.

[20] Wang J, Xu F, Jin H, Chen Y, Wang Y. Non-noble metal-based electrocatalysts for hydrogen evolution reaction. Chem Rev 2020;120(15):9021–92.
[21] Ingle AA. Oxy-hydrogen gas generator design and development for SI engine. International Research Journal of Engineering and Technology (IRJET) 2021;8 (10):1283–91. https://doi.org/10.6100/IRJET.V8I10.100320.
[22] Lodhi R, Ahmad N, Ahmed R. An empirical study for achieving economies of scale by utilization of (HHO) hydrogen hydroxy gas as additional fuel. Journal of Energy Technology Policy 2015;5(4). https://doi.org/10.5897/JETP2015.0123. 2225–0573.
[23] De Silva YSK, Middleton PH, Kolhe ML. Performance comparison of mono-polar and bi-polar configurations of alkaline electrolysis stack through 3-D modelling and experimental fabrication. Renew Energy 2020;149:760–72. https://doi.org/10.1016/j.renene.2019.12.068.
[24] Davis ME, Davis RJ. Fundamentals of chemical reaction engineering. Courier Corporation 2012.
[25] Bakker MM, Vermaas DA. Gas bubble removal in alkaline water electrolysis with utilization of pressure swings. Electrochim Acta 2019;319:148–57. https://doi.org/10.1016/j.electacta.2019.07.058.
[26] Singh R, Kumar S, Sharma A. Hydrogen production using water electrolysis: a comprehensive review. Energy Rep 2021;7:1022–37. https://doi.org/10.1016/j.egyr.2021.02.002.
[27] Patel KK, Singhal T, Pandey V, Sumangala TP, Sreekanth MS. Evolution and recent developments of high performance electrode material for supercapacitors: a review. J Energy Storage 2021;44:103366.
[28] Chang B, Wu S, Wang Y, Sun T, Cheng Z. Emerging single-atom iron catalysts for advanced catalytic systems. Nanoscale Horizons 2022;7(11):1340–87.
[29] Gohar GA, Hassan R. Comparative analysis of performance characteristics of CI engine with and without HHO gas (Brown Gas). Adv Automob Eng 2017;6(172):2.
[30] El Kady MA, Farrag AEF, Gad MS, El Soly AK, Hashish HA. Parametric study and experimental investigation of hydroxy (HHO) production using dry cell. Fuel 2020; 282:118825.
[31] Göllei A. Measuring and optimisation of HHO dry cell for energy efficiency. Acta Tech. Corvin. 2014;7(4):19.
[32] Chen R, Jin Y, Zhang T, Wang X. Influence of electrolyte composition on the performance and stability of hydrogen production systems. Energy Rep 2021;7: 4593–605.
[33] Thangaraj S, Govindan N. Investigating the pros and cons of Brown's gas and varying EGR on combustion, performance, and emission characteristics of a diesel engine. Environ Sci Pollut Control Ser 2018;25(1):422–35. https://doi.org/10.1007/s11356-017-0426-5.
[34] Coats KH, Richardson JG. Calculation of water displacement by gas in the development of aquifer storage. Soc Petrol Eng J 1967;7(2):105–12. https://doi.org/10.2118/1676-PA.
[35] Lee S, Park J. Effectiveness of various electrolytes in the electrolysis of water. Electrochim Acta 2020;342:135484. https://doi.org/10.1016/j.electacta.2020.135484.
[36] Cherevko S, Geiger S, Kasian O, Kulyk N, Grote JP, Savan A, Mayrhofer KJJ. Oxygen and hydrogen evolution reactions on Ru, RuO_2, Ir, and IrO_2 thin film electrodes in acidic and alkaline electrolytes: a comparative study on activity and stability. Catal Today 2016;262:170–80.
[37] Xiang R, Wang X. Advanced self-standing electrodes for water electrolysis: a review on strategies for further performance enhancement. Chemelectrochem 2022;9(9): e202200029.
[38] Danilovic N, Subbaraman R, Chang KC, Chang SH, Kang YJ, Snyder J, Markovic NM. Activity–stability trends for the oxygen evolution reaction on monometallic oxides in acidic environments. J Phys Chem Lett 2014;5(14):2474–8.
[39] Stolten D, Emonts B, editors. Hydrogen science and engineering, 2 volume set: materials, processes, systems, and technology, vol. 1. John Wiley & Sons; 2016.
[40] Zeng K, Zhang D. Recent progress in alkaline water electrolysis for hydrogen production and applications. Prog Energy Combust Sci 2010;36(3):307–26.
[41] Tawalbeh M, Farooq A, Martis R, Al-Othman A. Optimization techniques for electrochemical devices for hydrogen production and energy storage applications. Int J Hydrogen Energy 2024;52:1058–92.