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HYDROGEN STORAGE IN TROPICAL CLIMATES: A REVIEW OF SAFE STORAGE METHODS FOR NIGERIA

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Highlights:

- *Metal hydrides are safest, most efficient hydrogen storage for Nigeria's climate.*
- *Tropical conditions demand durable, corrosion-resistant storage solutions.*
- *Hydrogen storage supports Nigeria's shift to renewable energy and energy security.*
- *Compressed gas storage scores high on scalability but low on durability.*
- *Localized cooling and hybrid systems show promise for tropical deployment.*

Abstract: This review explores hydrogen storage methods with a focus on their suitability for Nigeria's tropical climate, which presents unique environmental challenges such as high humidity, temperature fluctuations, and limited cold storage infrastructure. The objective of the study is to identify hydrogen storage solutions that are both technically viable and contextually appropriate for Nigeria, supporting the nation's transition toward cleaner energy sources. The scope of the review encompasses both physical-based and material-based storage methods. A comparative evaluation was conducted using a structured, literature-based qualitative multi-criteria decision analysis framework that assessed each method based on safety, energy efficiency, cost-effectiveness, scalability, and long-term durability under tropical conditions. The findings reveal that while compressed gas remains the most established technology, it can pose risks under high ambient temperatures. Liquid hydrogen and cryo-compressed options were found to be energy-intensive and logistically challenging for tropical deployments. Among material-based methods, metal hydrides emerged as the most promising due to their thermal stability, compactness, and safer handling features. The study concludes that metal hydrides, particularly those tailored for moderate temperature operation, offer a strategic pathway for hydrogen storage in Nigeria. The review highlights the importance of local adaptation, calling for policies and research focused on climate-adapted technologies, integration with Nigeria's renewable energy sources, and investment in infrastructure. These findings provide critical insights for stakeholders aiming to develop a sustainable hydrogen economy in tropical regions.

Keywords: energy storage; hydrogen storage; Nigeria; tropical climate

1. Introduction

Hydrogen possesses a high specific energy of 141.9 kJ per gram, making it significantly more energy-dense than natural gas which is 54 kJ per gram and gasoline which is 47 kJ per gram (Nanda et al., 2017). When combusted, hydrogen produces only water vapor as a byproduct. It can be derived from multiple sources, including hydrocarbons, water, and organic materials (Megía et al., 2021). Hydrogen’s low molecular weight, high energy yield, and ease of storage make it a viable solution for future energy needs. Given its excellent energy efficiency and zero carbon footprint, hydrogen is increasingly being viewed as a promising alternative in the global transition toward environmentally friendly energy systems (Becherif et al., 2015; Bhandari & Adhikari, 2024; Le et al., 2024; Mazloomi & Gomes, 2012; Ren et al., 2017; Schitea et al., 2019; Wagemans et al., 2005).

Recent studies (Le et al., 2024) highlight hydrogen's essential role as an energy storage solution that complements variable renewable systems, such as wind and solar, which frequently struggle to match supply with demand consistently. Among available solutions, hydrogen stands out as a cost-efficient method for storing electrical energy over extended periods. Unlike electricity, which typically requires immediate consumption, hydrogen can be stored and used when needed, offering flexibility in managing the gap between generation and usage (Gulraiz et al., 2025).

Hydrogen is a promising, versatile clean fuel that could help address Nigeria's energy challenges. However, its widespread use is limited by the difficulty of storing it safely and efficiently, especially in a tropical climate.

Nigeria’s climate is distinctly tropical, characterized by significant variations in temperature and humidity across its different ecological zones. The southern regions experience a tropical monsoon climate with an average temperature range of 25°C to 32°C and high relative humidity that can exceed 85%, while the drier northern regions have temperatures that can reach over 38°C (Onafeso, 2023). The high temperatures and persistent humidity in Nigeria pose significant challenges to hydrogen storage technologies. High temperatures can cause hydrogen-assisted thermal aging, which degrades storage materials and leads to reduced system efficiency and increased safety risks (Habib et al., 2023). Similarly, high humidity can accelerate corrosion and negatively impact the performance and lifespan of fuel cells (Chen et al., 2025).

The combination of these climate-specific factors with Nigeria's existing infrastructural and economic limitations creates a pressing need for durable and cost-effective storage solutions.

The application of hydrogen as a workable energy source will continue to be restricted if these issues are not resolved.

This review aims to critically examine existing hydrogen storage technologies and assess their suitability within Nigeria’s tropical climate conditions. The scope of the study includes both physical and material-based storage methods, with a focus on evaluating their performance in high-temperature and high-humidity environments. By identifying the most promising and context-appropriate storage options, this paper provides insights to guide policy, research, and infrastructure development for hydrogen deployment in Nigeria and similar tropical regions.

2. Literature Review

An essential component of the hydrogen energy process is storage, impacting its efficiency, safety, and scalability. For the energy shift to include renewable hydrogen, its storage and transportation are essential for making renewable hydrogen a reality in achieving net-zero emissions goals (Le et al., 2024; Yang et al., 2023).

Storing Hydrogen is an essential phase in ensuring a steady supply of hydrogen fuel. Many believe it is the hardest part of creating a hydrogen-based economy (Durbin & Malardier-Jugroot, 2013; Edwards et al., 2007; Eftekhari & Fang, 2017; Jia et al., 2015; Prabhukhot et al., 2016; Ren et al., 2017; Rusman & Dahari, 2016; Webb, 2015). According to Yang et al. (2023), the way hydrogen is stored affects both its transportation method and how it is used.
Right now, storing hydrogen is still a challenge in hydrogen energy applications (Le et al., 2024; Okolie et al., 2021). Green hydrogen's low energy density makes it challenging to store, particularly when it comes to transit or use in fuel tanks. These tanks must be big, have a lot of volumetric and gravimetric storage space, be inexpensive, light, and have good adsorption and desorption capabilities. Systems for storing hydrogen might be material-based or physical. Hydrogen can be preserved either in a compressed gaseous state using high-pressure containers or as a cryogenic liquid at very low temperatures. Several advanced materials have shown potential for this purpose, including metal–organic frameworks (MOFs), porous zeolites,

carbon-based nanostructures, and microscale hollow spheres (Le et al., 2024 and Yang et al., 2023).

Kojima et al. (2013) classify hydrogen storage materials into two main categories: those that rely on chemisorption and those that utilize physisorption. Both types present unique advantages and limitations. Ideally, such materials should be widely available, cost-effective, and safe, with fast reaction kinetics and easy handling. They should also offer substantial hydrogen storage capacity by both weight and volume, along with favorable thermodynamic characteristics that allow for efficient and reversible absorption and release of hydrogen.
Since all six of the storage techniques being studied call for materials that either react strongly with hydrogen or do not at all, Züttel (2003) notes that hydrogen storage poses a materials science issue. The capacity to reversibly absorb and release hydrogen is a crucial component of hydrogen storage. Therefore, both reactive and inert materials play a critical role in developing efficient storage systems (Züttel, 2003; Pistidda, 2021).

Physical hydrogen storage systems often rely on materials characterized by extensive surface area, numerous adsorption sites, and strong energy storage capacity relative to their mass. Examples of such materials include hollow nanospheres, carbon-derived structures, porous zeolites, and MOFs. These characteristics contribute to their effectiveness and adaptability in storing hydrogen. Moreover, factors like ease of production, cost efficiency, and chemical durability make them highly practical. Ongoing advancements have further enhanced these materials, enabling greater hydrogen uptake even under ambient conditions (Khalili et al., 2025; Mekonnin et al., 2025).

However, significant challenges persist. Many materials require cryogenic conditions for optimal performance, which increases energy costs and reduces practicality. Other drawbacks include low volumetric energy density, deficiencies in binding site efficiency, and difficulties in controlling pore structures. Complex fabrication processes and limited tunability further hinder their widespread adoption. While certain materials demonstrate high hydrogen storage density, their reliance on low temperatures limits their applications compared to chemical hydrogen storage options (Mekonnin et al., 2025; Khalili et al., 2025).

In tropical climates, high humidity and elevated temperatures exacerbate these challenges. Elevated temperatures lower storage density and create thermal stress, increasing the risk of pressure buildup in storage systems. Humidity accelerates material degradation, particularly in systems using porous materials such as MOFs, where water molecules interfere with adsorption capacity and storage efficiency. Effective moisture management, while possible through advanced insulation techniques, complicates system design and increases maintenance demands (Bhandari & Adhikari, 2024).

Developing economies, including Nigeria, face additional barriers such as limited access to advanced materials and technical expertise, as well as high upfront costs for state-of-the-art solutions. Supply chain limitations and infrastructure gaps further hinder the adoption of hydrogen storage systems. However, promising approaches include hybrid storage systems, localized cooling methods, and renewable energy integration, such as solar-powered cryogenic storage. These strategies, alongside ongoing research, demonstrate potential to address current limitations and adapt hydrogen storage technologies for tropical and economically constrained regions (İlbahar et al., 2022; Khalili et al., 2025).

Advancements in material science and system design are vital for establishing hydrogen storage as a fundamental element of a sustainable energy future. By addressing efficiency, cost, and scalability challenges, these innovations could make hydrogen storage systems viable even in the most demanding environments (Mekonnin et al., 2025; Khalili et al., 2025).

In addition, transportation remains a critical gap that requires further review. Efficient and safe movement of hydrogen, whether as compressed gas, liquid, or in solid-state carriers, is particularly challenging under tropical conditions, where long distances, inadequate infrastructure, and high ambient temperatures intensify safety and cost concerns (Mekonnin et al., 2025).

2.1. Storage of Hydrogen

Yang et al. (2023) outlined two main categories of hydrogen storage methods: those that rely on materials and those based on physical processes (see Figure 1). In the latter, hydrogen is preserved by changing its physical condition, either by cooling it to cryogenic temperatures for liquid hydrogen (LH_2), compressing it into high-pressure gas (CGH_2), or applying both methods simultaneously in cryo-compressed hydrogen storage. In contrast to physical-based techniques, material-based storage uses unique materials that function as "carriers," forming chemical or physical bonds with hydrogen to increase storage density and safety. However, testing and development are still ongoing for the majority of material-based storage solutions. For a successful hydrogen economy, storage systems must prioritize safety, efficiency, cost-effectiveness, and be both lightweight and compact (İlbahar et al., 2022; Zhang et al., 2015, 2017).

The six hydrogen storage techniques that we will look at are listed below. The subsequent techniques are material-based, while the first two are physical (Mekonnin et al., 2025).

1. Compressed gas storage
2. Liquid hydrogen storage
3. Surface adsorption
4. Metal hydrides
5. Complex hydrides
6. Chemical storage

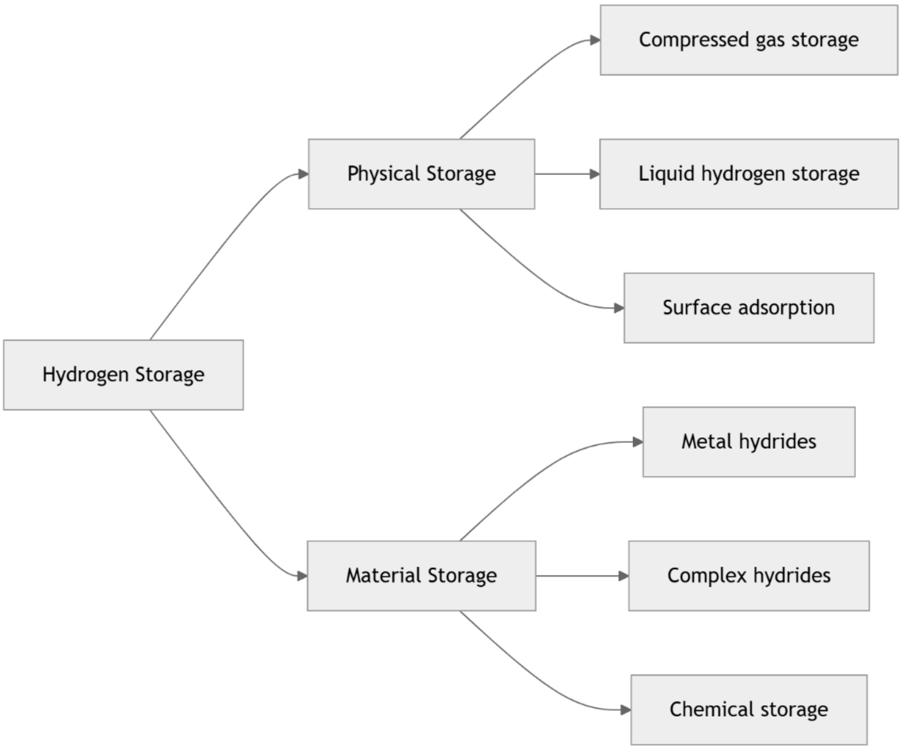

Figure 1: An overview of methods used for hydrogen storage.

Source: Liu et al. (2020)

2.1.1. Compressed Gas Storage

One of the most widely used approaches for hydrogen storage involves compressing the gas and containing it in reinforced cylindrical vessels at pressures around 200 bar. These containers are typically crafted from durable materials such as advanced metal blends or composite structures to endure the stress of high internal pressure. As noted by Makridis (2016), the ability of these storage units to handle higher pressure depends significantly on the material's resistance to tension. With the advancement of lightweight composite tanks capable of handling pressure levels up to 800 bar, hydrogen can now be compacted to a density of 36 kg/m³, roughly 50% of what it would be in its liquid state at boiling temperature.

For medium- and extended-duration storage, hydrogen can be retained as a gas in underground facilities, providing both cost-effective and environmentally friendly solutions. Geological formations such as aquifers, porous rock layers, salt domes, and exhausted oil and gas fields are commonly utilized for this purpose. Exhausted oil and gas fields are particularly beneficial due to their established ability to contain gases and the existing infrastructure, whereas aquifers and porous rock formations present alternative storage possibilities, depending on their geological conditions. Salt caverns, although requiring artificial creation through solution mining, provide excellent impermeability and operational efficiency. Each method presents unique benefits and challenges, but collectively, they draw attention to the possibility of storing hydrogen underground to meet the rising energy needs of a sustainable hydrogen economy. (Epelle et al., 2022; Keçebaş & Kayfeci, 2019).

2.1.2. Liquid Hydrogen Storage

Another method of hydrogen storage involves converting it into a cryogenic liquid by lowering its temperature to -253°C. This approach is widely used in both space missions and large-scale industrial processes because it provides a much higher volumetric energy density compared to compressed hydrogen gas (Bouramdane, 2024; Midilli et al., 2005; Webb, 2015).

When compared to hydrogen gas stored at 700 bar (1.3 kWh/L) or 350 bar (0.8 kWh/L), liquid hydrogen offers a substantial increase in energy density, reaching 2.2 kWh/L (Hirscher, 2010). However, one significant challenge of liquid hydrogen storage is its energy-intensive cooling process, as it requires a substantial amount of energy, around 30% of the hydrogen's total energy content,to maintain the low temperature necessary for liquid form (Midilli et al., 2005; Webb, 2015).

2.1.3. Surface Adsorption

Hydrogen physisorption involves the reversible binding of H_2 molecules to solid surfaces via weak van der Waals interactions, enabling subsequent release for applications such as fuel cells (Ali et al., 2024; Milanese et al., 2019). This mechanism is particularly attractive due to its fast kinetics and full reversibility under mild conditions.

Nanostructured carbon materials, especially single-walled carbon nanotubes (SWCNTs), graphene, and activated carbons, remain leading candidates due to their high specific surface areas and tunable pore structures (Gadipelli et al., 2020). Recent experimental work confirms that at cryogenic temperatures (77 K), SWCNTs can achieve hydrogen uptakes approaching 3.0 wt%, correlating with surface areas near 1300–1500 m²/g (Ali et al., 2024; Romanos et al., 2018). At ambient temperatures (298 K), however, capacities drop significantly, typically below 0.5–1.0 wt% even under high pressure (100 bar), due to the weak adsorption enthalpies (~4–6 kJ/mol) and hydrogen's low critical temperature (33 K) (Khalili et al., 2025).

Contrary to early assumptions, recent studies show that nanotube curvature has only a marginal effect on total hydrogen uptake; instead, accessible surface area and optimal pore size (0.6–0.7 nm) dominate performance (Gadipelli et al., 2020; Romanos et al., 2018). Attempts to enhance storage via internal nanotube filling or covalent functionalization have yielded minimal gains and often compromise reversibility (Yang et al., 2023). In situ spectroscopic and gravimetric analyses confirm that adsorption/desorption is fully reversible without pore condensation or hysteresis, affirming the physisorptive nature of the process (Ali et al., 2024; Khalili et al., 2025).

While physisorption systems offer advantages, low cost, rapid cycling, and mechanical simplicity, their practical deployment remains limited by the need for cryogenic cooling or very high pressures to achieve meaningful storage densities (Khalili et al., 2025; McQueen et al., 2020). Current research focuses on metal-organic frameworks (MOFs) and doped carbons to enhance binding energy while preserving reversibility, a critical step toward ambient-temperature operation (Ali et al., 2024; Milanese et al., 2019; Gadipelli et al, 2020).

2.1.4. Metal Hydrides

When hydrogen combines with certain metals or alloys, it forms stable metal hydrides capable of reversibly absorbing and releasing hydrogen gas. These compounds enable efficient storage at moderate pressures and relatively low temperatures. Solid-state storage via metal hydrides is considered the safest method, offering high volumetric density and minimal leakage risk (Yang et al., 2023). Due to their stability and capacity, metal hydrides are increasingly adopted in fuel cell vehicles and industrial energy systems (Klopčič et al., 2023; Von Colbe et al., 2019; Yang et al., 2023).

Magnesium hydride (MgH_2) and titanium-based alloys are among the most widely studied. MgH_2 offers high capacity (7.6 wt%) but requires kinetic and thermodynamic improvements, now being addressed via catalytic doping and nanostructuring (Liu et al., 2020). Titanium alloys such as TiFe operate near ambient conditions and show improved activation and hysteresis behavior with elemental substitution (Yang et al., 2023).

2.1.5. Complex Hydrides

Due to their high hydrogen-to-metal ratios and low atomic weights, complex hydrides are promising candidates for hydrogen storage. These compounds typically involve light elements from Groups 1–3, such as lithium, magnesium, boron, and aluminum, which form hydrogen-rich anions stabilized by alkali or alkaline earth cations (Ali et al., 2024).

Unlike metallic hydrides, which feature ionic or metallic bonding, complex hydrides contain covalently bonded hydrogen within polyatomic anions (e.g., $[BH_4]^-$, $[AlH_4]^-$), often arranged in tetrahedral geometries around central atoms like B or Al. Charge balance is maintained by cations such as Li^+ or Na^+ (Liu et al., 2020).

Key materials include:
$NaAlH_4$: When catalyzed (e.g., with Ti), it reversibly releases up to 4.2 wt% H_2, with near-flat pressure plateaus between 180–210 °C (Yang et al., 2023).
$LiBH_4$: Offers the highest known gravimetric capacity (18 wt%) among solid-state materials at ambient pressure, though decomposition requires elevated temperatures (>380 °C) and suffers from slow kinetics and irreversibility without modification (Milanese et al., 2019; Von Colbe et al., 2019).

While thermodynamic and kinetic barriers remain challenges, recent advances in destabilization, nanoconfinement, and catalytic additives have improved reversibility and lowered operating temperatures, renewing interest in complex hydrides for practical systems (Ali et al., 2024; Milanese et al., 2019).

2.1.6. Chemical Storage

Hydrogen can be generated via chemical reactions between reactive metals (e.g., Na, Li) and water, yielding hydrogen gas and metal hydroxides. While inherently irreversible under ambient conditions, the hydroxide by-products can be regenerated to metallic form using high-temperature reduction, for instance, via concentrated solar thermal systems (Ali et al., 2024; Yang et al., 2023). The reaction $2Na + 2H_2O \rightarrow 2NaOH + H_2$ exemplifies this process; the liberated H_2 can be used in fuel cells or combustion, re-forming water.

Lithium offers a higher theoretical hydrogen yield (6.3 wt%) than sodium (3.0 wt%), making it more attractive gravimetrically, though cost and reactivity challenges persist (Milanese et al., 2019; Von Colbe et al., 2019). Recent research focuses on system-level efficiency, regeneration energy penalties, and integration with renewable heat sources.

Table 1: Pros and Cons of Different Hydrogen Storage Methods.

Method	Pros	Cons
Compressed gas storage	- Mature technology with established commercial applications - Scalable for various applications - New lightweight cylinders withstand pressures up to 800 bar, achieving 36 kg/m³ density	- Energy-intensive compression reduces overall efficiency - Safety concerns due to high pressure - Material fatigue and corrosion, especially in humid environments
Liquid hydrogen storage	- High volumetric density (2.2 kWh/L) - Proven use in aerospace and large-scale industrial applications	- Requires extreme cooling to -253°C with continuous energy input - Risk of vaporization and pressure buildup - Cryogenic temperatures degrade some materials
Surface adsorption	- Low operating pressure improves safety - Cost-effective materials (e.g., CNTs) - Simple system design	- Low gravimetric and volumetric hydrogen density - Effective only at cryogenic temperatures (e.g., 77 K) - Limited storage capacity
Metal hydrides	- High storage density with moderate operating pressures - Solid-state storage ensures safety - Stable under various conditions	- High heat requirements for hydrogen release - Susceptibility to degradation in humid conditions - Relatively high material cost
Complex hydrides	- High hydrogen density (e.g., $LiBH_4$ with 18 mass%) - Stability at elevated temperatures - Reactions can be catalyzed for efficiency	- High decomposition temperatures (up to 280°C) - Limited reversibility of some hydrides - Requires precise material design to balance stability and performance

Chemical storage	- High gravimetric hydrogen densities (e.g., Li with 6.3 mass%) - Renewable process possible through solar-driven reduction - Versatile across metals like Na and Zn	- Irreversible reactions limit direct reuse - High energy demands for thermal reduction - Efficiency losses from water and heat requirements

3. Materials and Methods

This study adopts a comparative review methodology to evaluate hydrogen storage methods with respect to their suitability for Nigeria's tropical climate. The analysis focuses on the advantages, performance, feasibility, and limitations of six established storage technologies, compressed gas storage, liquid hydrogen storage, surface adsorption, metal hydrides, complex hydrides, and chemical storage, while explicitly considering environmental, economic, and infrastructural constraints unique to high-temperature, high-humidity regions. The evaluation is guided by five key criteria: safety, energy efficiency, cost-effectiveness, scalability, and durability under tropical conditions. These were selected based on their documented importance in hydrogen storage literature and their direct relevance to operational challenges in tropical environments, including thermal stress, material corrosion from humidity, and limited cryogenic infrastructure (Mekonnin et al., 2025). To enable structured comparison across these heterogeneous technologies, a qualitative multi-criteria decision analysis (MCDA) framework was applied. This approach is widely used in energy technology reviews when empirical, site-specific experimental data are unavailable or insufficient for direct quantitative comparison (Khalili et al., 2025; Mekonnin et al., 2025). Each criterion was scored on a relative scale from 1 (poor) to 5 (excellent), informed by synthesized evidence from peer-reviewed studies on each storage method's behavior under elevated temperature and humidity conditions. Scores were assigned through expert-informed judgment calibrated against consensus findings in the literature. For example: High safety scores for metal hydrides reflect documented solid-state containment properties reducing leak risks (Yang et al., 2023; Rusman & Dahari, 2016), Low durability scores for compressed gas systems account for well-documented fatigue and corrosion issues in humid climates (Tzimas et al., 2003; Durbin & Malardier-Jugroot, 2013), Low efficiency scores for liquid hydrogen stem from its known energy-intensive liquefaction process and boil-off losses under ambient tropical heat (Barthélémy, 2012; Mazloomi & Gomes, 2012). While this method does not involve laboratory measurements, sensor data, or computational modeling, it provides a transparent, systematic, and reproducible means of comparing technologies where primary field data in tropical contexts remain scarce. All scores are derived entirely from aggregated trends reported across multiple published sources and reflect relative performance patterns observed in the broader scientific literature. The resulting scores, summarized in Table 2, are intended solely for comparative prioritization within the scope of this review. They are not predictive, nor do they claim absolute accuracy. Rather, they serve as an interpretive tool to identify the most contextually appropriate storage solutions for Nigeria's specific climatic and developmental profile.

4. Comparative Analysis and Results

Following the MCDA framework outlined in Section 3, each hydrogen storage method was evaluated across five criteria, safety, efficiency, cost-effectiveness, scalability, and durability under tropical conditions, and scored from 1 (poor) to 5 (excellent). Scores were derived not from experimental measurements, but from synthesized consensus findings in the peer-reviewed literature, as detailed in Section 3.

Table 2 provides a summary of the results.

Table 2: Comparative Evaluation of Hydrogen Storage Methods.

Storage Method	**Safety**	**Efficiency**	**Cost-Effectiveness**	**Scalability**	**Durability**	**Total Score**
Compressed gas storage	3	3	3	5	3	17
Liquid hydrogen storage	3	5	2	3	2	15
Surface adsorption	4	4	3	2	4	17
Metal hydrides	5	4	3	3	4	19
Complex hydrides	4	4	3	3	4	18
Chemical storage	4	3	3	3	4	17

Metal hydrides achieved the highest total score (19), primarily due to their solid-state nature, which minimizes leak risks (safety = 5) and demonstrates superior resilience to thermal stress and humidity-induced degradation (durability = 4). Recent studies confirm that Mg- and Ti-based alloys, when modified with catalysts or nano-structuring, maintain reversible hydrogen uptake at moderate temperatures (50–150°C), making them uniquely suited to Nigeria's ambient climate without requiring cryogenic infrastructure (Yang et al., 2023; Rusman & Dahari, 2016; Abe et al., 2019). While material costs remain higher than compressed gas and scalability is moderate, their operational stability and safety profile make them the most viable option for near-term deployment.

Complex hydrides scored 18, benefiting from exceptional gravimetric capacity (e.g., $LiBH_4$ at 18 wt%) and inherent thermal stability. However, their high desorption temperatures (>250°C) and sensitivity to moisture significantly limit practicality in humid, low-infrastructure settings common in Nigeria. Recent work by Zhang & Wu (2017) highlights that while catalytic doping improves kinetics, long-term reversibility remains challenging under fluctuating environmental conditions, a critical barrier in tropical climates.

Surface adsorption, chemical storage, and compressed gas storage each scored 17. Surface adsorption systems (e.g., MOFs, CNTs) offer safety and simplicity but suffer from low volumetric density and severe performance loss in humid environments due to competitive water adsorption, a well-documented limitation in recent reviews (Megía et al., 2021; Bhandari & Adhikari, 2024). Chemical storage methods, such as lithium-water reactions, provide high gravimetric density (6.3 wt%), but require energy-intensive regeneration of chemical byproducts (e.g., $NaOH \rightarrow Na$), a process still reliant on fossil-fueled heat sources in developing economies (Züttel, 2003; Le et al., 2024). Compressed gas storage remains scalable and mature, yet its vulnerability to corrosion and pressure-related fatigue in hot, humid climates is consistently cited as a major drawback (Durbin & Malardier-Jugroot, 2013; Epelle et al., 2022).

Liquid hydrogen, despite its high volumetric energy density (2.2 kWh/L), received the lowest overall score (15). Its extreme energy penalty for liquefaction (~30% of stored hydrogen's energy content) and persistent boil-off losses under sustained ambient temperatures >30°C render it logistically unfeasible without advanced cryogenic infrastructure, a reality absent in most Nigerian contexts (Barthélémy, 2012; Mazloomi & Gomes, 2012; Le et al., 2024).

In summary, metal hydrides emerge as the most contextually appropriate solution for Nigeria's tropical climate, offering the optimal balance of safety, durability, and operational feasibility under existing infrastructural constraints. While other methods show promise in specific domains, none match the robustness of metal hydrides across all five evaluation criteria. Future efforts should prioritize local alloy development, waste-heat integration, and pilot-scale demonstration projects to bridge the gap between laboratory potential and field readiness.

5. Conclusions

Hydrogen storage presents a critical pathway for Nigeria's energy transition, particularly under its tropical climate conditions where high temperatures and humidity challenge conventional technologies. This review has evaluated six storage methods using a structured, literature-based qualitative MCDA framework, assessing each against safety, efficiency, cost-effectiveness, scalability, and durability, criteria directly relevant to Nigeria's operational context.

Among the options examined, metal hydrides emerged as the highest-scoring method (19/25), primarily due to their solid-state nature, which inherently reduces risks associated with pressure and leakage, and their demonstrated resilience under thermal stress and humid environments. These attributes make them a compelling first consideration for deployment in Nigeria, especially where infrastructure limitations rule out cryogenic or ultra-high-pressure systems.

Other methods also hold value depending on application. Compressed gas storage remains widely accessible and scalable, though its durability under prolonged heat and humidity remains a concern. Liquid hydrogen offers high volumetric density but demands significant energy input and infrastructure that is currently impractical in most Nigerian settings. Surface adsorption and chemical storage show promise in specific niches but are limited by low capacity or regeneration complexity. Complex hydrides offer high theoretical capacity but face challenges in reversibility and moisture sensitivity.

The scoring system applied here does not claim absolute superiority, rather, it reflects a relative prioritization based on aggregated evidence from peer-reviewed studies under tropical conditions. Metal hydrides are not perfect; they carry higher material costs and require moderate thermal management. But within the constraints of Nigeria's climate and current technological readiness, they represent the most balanced option available today.

Looking ahead, future efforts should focus on adapting metal hydride materials, such as Mg- and Ti-based alloys, for lower desorption temperatures and improved humidity resistance, ideally through local R&D partnerships. Integration with solar PV for endothermic hydrogen release could further enhance viability in off-grid areas. While innovations like biohydrogen production or repurposed gas infrastructure may shape long-term strategies, these lie beyond the scope of this technical comparison.

In summary, while no single storage solution is universally ideal, metal hydrides stand out as the most suitable candidate for initial deployment in Nigeria's tropical environment. Their performance across multiple criteria, particularly safety and durability, positions them as a pragmatic starting point for building a reliable, locally adapted hydrogen storage ecosystem. With targeted research and policy support, they can serve as a foundation upon which more advanced systems may be layered in the future.

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Credit Author Statement

Conceptualization, O.S. and I.T.; methodology, I.T. and M.E.; validation, D.E. and O.O.; formal analysis, O.S. and A.O.; investigation, O.S., I.T., and M.E.; data curation, O.S. and D.E.; writing—original draft preparation, O.S., I.T., and M.E.; writing—review and editing, O.S., D.E., O.O., and A.O.; visualization, O.S. and I.T.; supervision, O.S.; project administration, O.S.

Conflicts of Interest

The authors declare no conflict of interest.

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