International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
www.chemijournal.com
IJCS 2023; 11(5): 62-68

Received: 12-06-2023
Accepted: 18-07-2023

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Recent developments and emerging trends in hydrogen storage in liquid hydrogen carriers

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DOI: https://dx.doi.org/10.22271/chemi.2023.v11.i5a.12359

Abstract
Hydrogen, with its potential to revolutionize the energy landscape, stands at the forefront of sustainable solutions. Efficient storage of hydrogen is a pivotal challenge in realizing its full potential as an energy carrier. This review delves into recent developments and emerging trends in hydrogen storage, focusing specifically on liquid hydrogen carriers. The paper explores the advantages of liquid carriers, recent technological advancements, and the future trends shaping the landscape of hydrogen storage. As we stand on the cusp of a hydrogen-driven era, understanding the dynamics of liquid hydrogen carriers becomes imperative for unlocking a sustainable energy future.

Graphical abstract

Keywords: Liquid organic hydrogen carriers, hydrogen energy, storage, transportation, carrier

1. Introduction
The landscape of global energy is undergoing a profound transformation, fueled by the imperative to embrace sustainable practices. In this transition, hydrogen has emerged as a key protagonist, promising a clean and versatile energy carrier with the potential to reshape industries and power the future [1]. At the heart of harnessing hydrogen's potential lies the challenge of effective storage a prerequisite for unleashing its power across various applications. Hydrogen, as the simplest and most abundant element, possesses unique attributes that position it as a linchpin in the pursuit of green energy. Its significance as an energy carrier is underscored by its ability to serve as a clean fuel alternative in transportation, industry, and power generation. However, the transformative promise of hydrogen hinges on overcoming a critical hurdle-developing storage solutions that are not only efficient but also scalable and safe [1, 2].

The criticality of effective hydrogen storage cannot be overstated. As we navigate the complexities of a rapidly evolving energy landscape, the need for storage technologies that can accommodate the intermittent nature of renewable energy sources and provide a reliable energy supply becomes increasingly evident. Recent years have witnessed a significant shift in focus towards liquid hydrogen carriers as a viable solution to this storage challenge [3].

In light of these developments, this review seeks to provide a comprehensive exploration of recent advancements and emerging trends in hydrogen storage, with a particular emphasis on the transition to liquid hydrogen carriers. Our objectives are twofold: firstly, to succinctly summarize the latest breakthroughs in hydrogen storage technologies, and secondly, to delve into the nuanced landscape of liquid hydrogen carriers, identifying and analyzing the trends that are shaping their role in the future of hydrogen storage. Through this examination, we aim to contribute to the collective understanding of the current state of hydrogen storage and illuminate the trajectory it is poised to take in the years to come [4, 5].

2. Hydrogen Storage Methods Overview

As we embark on a comprehensive exploration of hydrogen storage methods, it is imperative to survey the existing landscape of technologies that facilitate the harnessing of hydrogen's potential as an energy carrier. The versatility of hydrogen is mirrored in the diverse array of storage methods available, each with its unique set of advantages and challenges.

2.1 Existing Hydrogen Storage Methods

Compressed hydrogen, a well-established method, involves storing hydrogen gas at high pressures. This method addresses the volumetric challenges posed by gaseous hydrogen, allowing for a more compact storage solution. Compressing hydrogen to high pressures, typically around 350–700 bar, facilitates its storage and transportation, making it a viable option for certain applications. However, challenges such as energy-intensive compression processes and the need for robust infrastructure have spurred exploration into alternative storage methods [6].

Liquid hydrogen stands as a time-tested method that involves cooling gaseous hydrogen to extremely low temperatures, around -253 degrees Celsius, to transition it into a liquid state. This process significantly reduces the volume occupied by hydrogen, making it a space-efficient storage solution. Liquid hydrogen has been widely employed in aerospace applications, but its energy-intensive liquefaction process and associated challenges have prompted a revaluation of its suitability for broader industrial and commercial use [7, 8].

Solid-state hydrogen storage methods involve chemically binding hydrogen to solid materials, providing a potentially safer and more compact storage solution. Various materials, such as metal hydrides and porous frameworks, have been explored for their hydrogen sorption capabilities. Solid-state storage offers advantages in terms of safety and ease of handling, but challenges related to weight, efficiency, and cost-effectiveness have been hurdles in its widespread adoption. As we navigate the intricate landscape of hydrogen storage methods, each approach presents a unique set of trade-offs. The subsequent sections of this review will delve deeper into the promising realm of liquid hydrogen carriers, shedding light on recent developments and emerging trends in this dynamic and evolving field [7]. Figure.1 shows various alternatives for hydrogen storage and transportation.

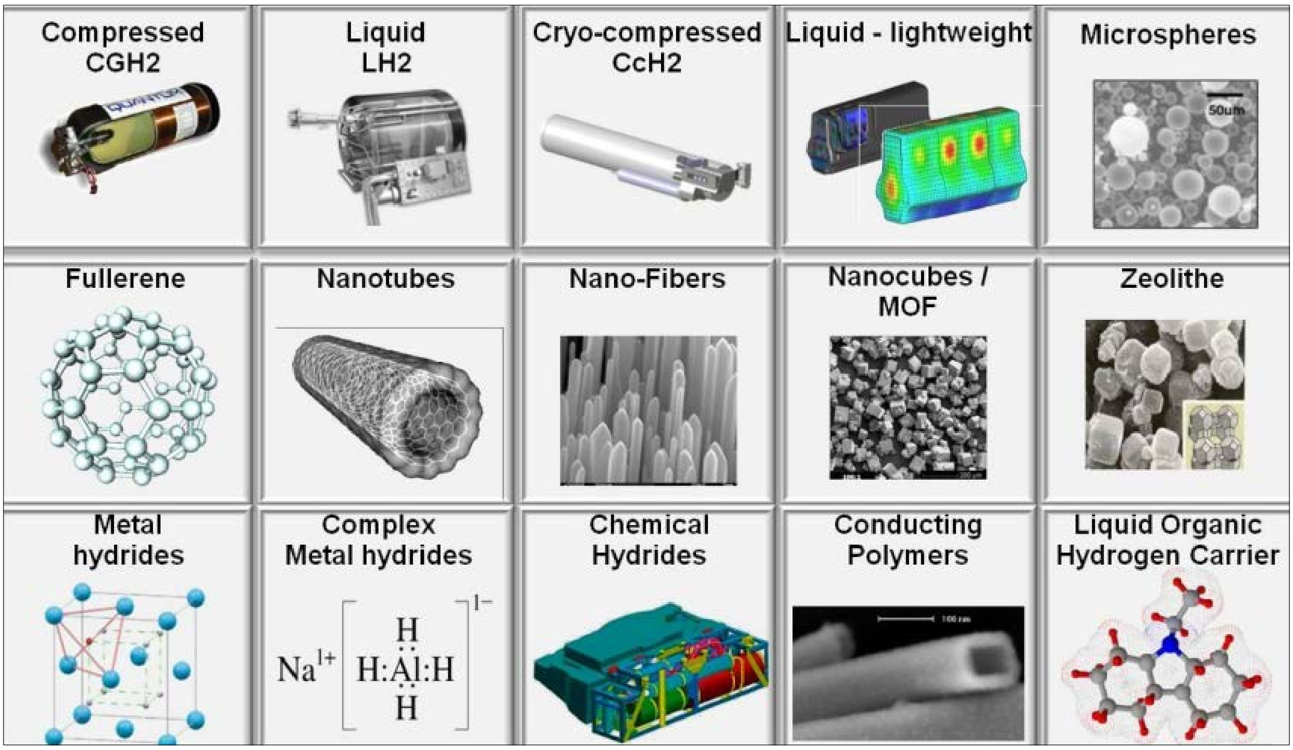

Fig 1: Different hydrogen storage alternatives [https://juser.fz-juelich.de/record/135562/files/HS2b_2_von-Wild.pdf]

2.2 Liquid organic hydrogen carriers (LOHCs)

Liquid Organic Hydrogen Carriers (LOHCs) stand out as a promising class of materials in the realm of hydrogen storage, offering innovative solutions to the challenges associated with the safe and efficient transportation of hydrogen. These materials, characterized by their capacity to absorb and release hydrogen reversibly, serve as molecular carriers that can capture and store hydrogen under certain conditions and release it when needed. The unique property of LOHCs lies in their ability to provide a dense and easily transportable form of hydrogen storage, addressing some of the key limitations of traditional storage methods. One notable characteristic of LOHCs is their high hydrogen storage capacity per unit volume. The molecular structure of these carriers allows them to bond with hydrogen in a chemically reversible process, facilitating efficient storage.

Dibenzyltoluene and perhydro-dibenzyltoluene are among the commonly studied LOHCs, showcasing their potential for storing significant amounts of hydrogen. This high volumetric capacity makes LOHCs an attractive option for applications where space efficiency is paramount, such as transportation and compact storage systems [8, 9].

Furthermore, the reversibility of the hydrogenation and dehydrogenation processes in LOHCs is a crucial feature. Table.1 shows Various Metal Based Monometallic and Bimetallic Catalysts Reported for Dehydrogenation of Liquid Organic Hydrides with their Hydrogen Evolution Rates. This reversibility enables the controlled release of hydrogen when needed, providing a responsive and on-demand supply of this clean energy carrier. The ability to release hydrogen under mild conditions enhances the safety and practicality of using LOHCs in various applications, contributing to the overall viability of hydrogen as a sustainable energy solution [10].

Table 1: Various Metal Based Monometallic and Bimetallic Catalysts Reported for Dehydrogenation of Liquid Organic Hydrides with their Hydrogen Evolution Rates

Reactant	Reactor System	Catalysts	Temp °C	H_2 Evolution Rate (mmol/g_{met}/min)
Cyclohexane	Batch-wise	5 wt% Pt/AC	82	0.034
Cyclohexane	Flow system	2 wt% Pt/Alumina	315	29
Cyclohexane	Flow system	12 wt% Pt-Rh/ACC	331	520
Cyclohexane	Flow system	11 wt% Pt-Re/ACC	328	550
Methyl Cyclohexane	Batch-wise	3.82 wt% Pt/ACC	300	610
Cyclohexane	Spray pulsed system	5 wt% Pt/AC	235	98
Cyclohexane	Spray pulsed system	0.5 wt % Pt/ACC*	300	0.22
Methyl cyclohexane	Spray pulsed system	1 wt% Pt/$La_{0.7}Y_{0.3}NiO_3$	350	45.76
Methyl cyclohexane	Spray pulsed system	3 wt% Pt/Al_2O_3	350	7.6
Methyl cyclohexane	Spray pulsed system	3 wt% Pt/Y_2O_3	350	966
Methyl cyclohexane	Spray pulsed system	3 wt% Pt/V_2O_5	350	330
Methyl cyclohexane	Spray pulsed system	10 wt% Pt/ACC	298	0.52
Cyclohexane	Spray pulsed system	10 wt% Ni/ACC	300	7.1
Cyclohexane	Spray pulsed system	20 wt% Ni/ACC	300	8.5
Cyclohexane	Spray pulsed system	20 wt% Ni -0.5 wt % t/ACC	300	13.1
Cyclohexane	Spray pulsed system	10 wt% Ag/ACC	300	6.9
Cyclohexane	Spray pulsed system	10 wt% Ag-1 wt% Pd/ ACC	300	7.5
Cyclohexane	Spray pulsed system	10 wt% Ag-1 wt% Rh/ ACC	300	12.34
Cyclohexane	Spray pulsed system	10 wt% Ag-1 wt% Pt/ ACC	300	13.36

2.3 Advantages of Liquid Hydrogen Carriers

Liquid hydrogen carriers present a spectrum of advantages that position them as a transformative solution in the landscape of hydrogen storage. At the forefront of these advantages is the higher energy density offered by liquid carriers compared to alternative storage methods. In contrast to gaseous or solid-state storage, liquid carriers allow for a more compact storage of hydrogen, significantly increasing the amount of energy that can be stored in a given volume. This heightened energy density not only addresses spatial constraints but also proves advantageous in applications where space efficiency is paramount, such as in the transportation sector [11]. Enhanced safety features represent another notable advantage of liquid hydrogen carriers. Recent advancements in technology have ushered in safety measures that mitigate concerns traditionally associated with handling and storing hydrogen. Liquid carriers offer a more controlled environment for hydrogen storage, reducing the risk of leaks or hazardous incidents. A comparative analysis with traditional storage methods reveals that liquid carriers, with their inherent containment properties, present a safer and more manageable option, fostering confidence in the broader adoption of hydrogen as a clean energy source [12, 13].

The potential for easier transportation is a pivotal advantage that further elevates the standing of liquid hydrogen carriers. The liquid state of hydrogen allows for more straightforward logistics and transportation, overcoming challenges associated with the volumetric expansion of hydrogen in its gaseous form. Exploration of the logistics and transportation benefits underscores the feasibility and practicality of incorporating liquid carriers into existing infrastructure. Case studies documenting successful transport using liquid carriers exemplify their adaptability and underline their potential to revolutionize supply chain dynamics, facilitating the widespread adoption of hydrogen across diverse sectors [3].

The advantages offered by liquid hydrogen carriers encompass higher energy density, improved safety features, and enhanced transportation feasibility. These attributes collectively contribute to the attractiveness of liquid carriers as a key enabler in advancing the use of hydrogen as a clean and efficient energy carrier. As research and development efforts continue to refine and optimize liquid carrier technologies, their role in shaping the future of hydrogen storage and utilization becomes increasingly pivotal [12, 13].

3. Recent Developments in Hydrogen Storage

Recent developments in hydrogen storage have witnessed a surge in technological advancements, particularly in the realm of liquid hydrogen carrier technologies. Breakthroughs in this area are proving instrumental in addressing the challenges associated with traditional storage methods. Researchers and engineers are actively exploring novel approaches to enhance the efficiency and scalability of liquid carriers. These advancements are pivotal in unlocking the full potential of hydrogen as a clean energy source. One of the focal points of recent technological advancements lies in the optimization of liquid hydrogen carrier technologies. Innovations in materials, design, and processes are pushing the boundaries of what was once deemed feasible. These breakthroughs aim to improve the storage capacity, release kinetics, and overall performance of liquid carriers. From engineered nanomaterials to advanced catalytic systems, researchers are leveraging cutting-edge technologies to propel liquid carriers into a new era of efficiency and effectiveness [14, 15].

Efficiency improvements and scalability represent key benchmarks in recent developments in hydrogen storage. Efforts are underway to streamline the hydrogenation and dehydrogenation processes associated with liquid carriers, minimizing energy losses and increasing overall system efficiency. Achieving scalability is crucial for the widespread adoption of these technologies, especially in industrial and commercial applications. Researchers are exploring innovative engineering solutions and process optimizations to make liquid carriers a practical and viable option for large-scale hydrogen storage and distribution networks. Moving beyond technological advancements, recent research papers have yielded valuable insights into the nuances of hydrogen storage [10]. Summarizing key findings reveals a growing understanding of the fundamental principles governing hydrogen-carrier interactions. Researchers are unraveling the complexities of thermodynamics, kinetics, and material science to design storage systems that are not only efficient but also economically viable. These findings provide a foundation for the continued evolution of hydrogen storage technologies [16, 17].

Moreover, recent research papers highlight innovative approaches to hydrogen storage that extend beyond traditional methods. From the integration of renewable energy sources to the exploration of advanced materials with tailored hydrogen sorption properties, the landscape is rich with diverse and imaginative solutions. These approaches signal a paradigm shift, emphasizing a holistic and multidisciplinary approach to the challenges of hydrogen storage. Recent developments in hydrogen storage are marked by notable technological breakthroughs in liquid carrier technologies, efficiency improvements, and scalability. The synthesis of findings from research papers offers a comprehensive understanding of the current state of hydrogen storage, while innovative approaches as shown in figure.2 pave the way for a future where hydrogen is harnessed and utilized with unprecedented efficiency and sustainability. The dynamic nature of this field ensures that ongoing research will continue to shape the trajectory of hydrogen storage technologies in the years to come [15].

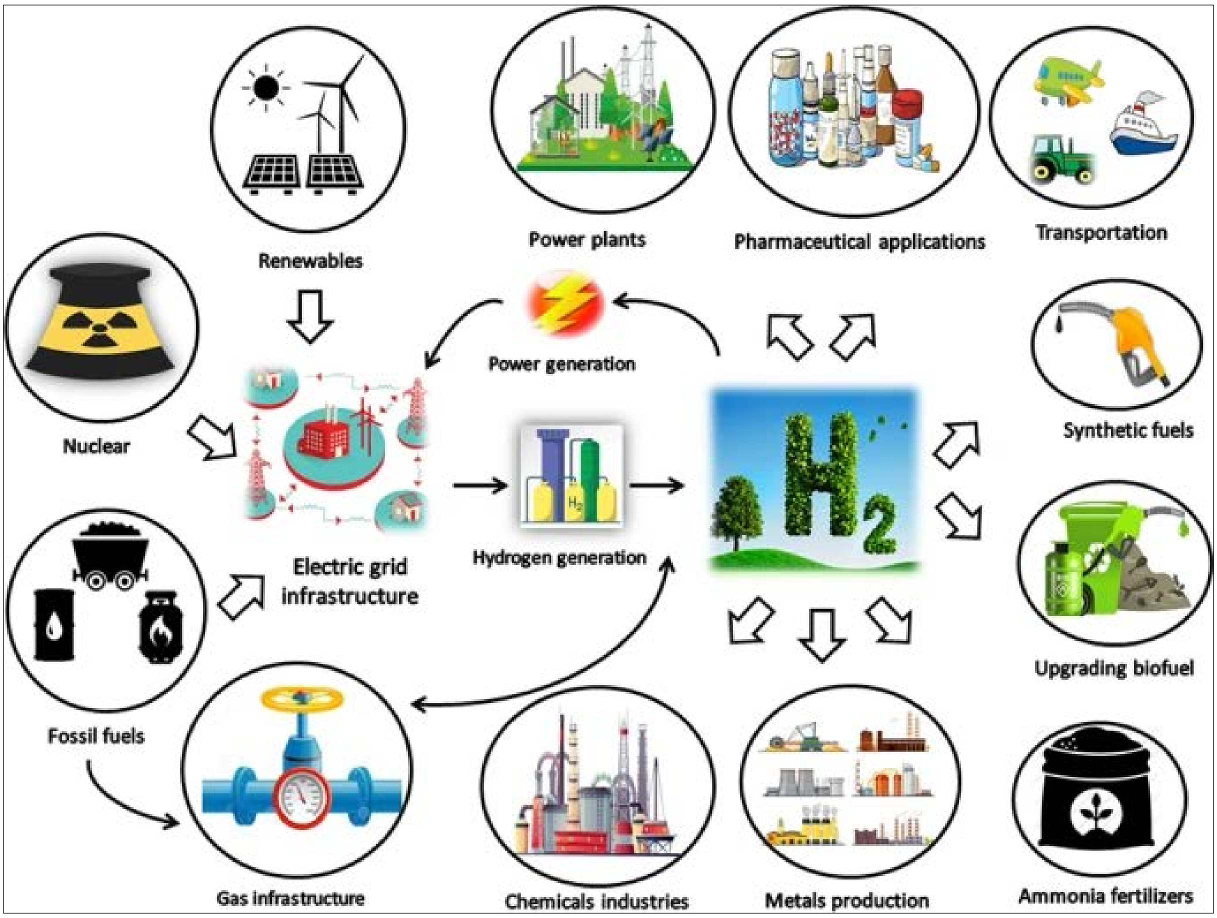

Fig 2: Hydrogen production routes, including renewables, fossil fuels and nuclear, with hydrogen being produced in power plants, pharmaceutical applications, synthetic fuels or their upgrades in transportation, ammonia synthesis, metal production or chemical industry applications [https://link.springer.com/article/10.1007/s10311-021-01322-8]

4. Emerging Trends in Hydrogen Storage

4.1 Technological innovations

Emerging trends in hydrogen storage are not only shaping the future but are also indicative of a paradigm shift towards more sustainable and integrated solutions. At the forefront of these trends are cutting-edge technological innovations that promise to redefine the landscape of liquid hydrogen carriers. Researchers and engineers are exploring revolutionary materials and design concepts, leveraging advancements in nanotechnology, catalysis, and materials science. These innovations aim to enhance the efficiency, safety, and economic viability of liquid carriers, positioning them as frontrunners in the quest for advanced hydrogen storage solutions. From engineered nanomaterials with superior hydrogen sorption capabilities to innovative reactor designs optimizing the hydrogenation and dehydrogenation processes, these cutting-edge technologies hold the key to unlocking the full potential of liquid carriers, paving the way for a more sustainable and accessible hydrogen economy [18, 19].

Integration with renewable energy sources is another pivotal trend that underscores the industry's commitment to achieving a truly green and sustainable hydrogen infrastructure. The synergy between hydrogen storage and renewables aligns with the broader goals of decarbonization and mitigating climate change. The ability to store excess energy produced from renewable sources, such as solar and wind, in the form of hydrogen provides a crucial avenue for overcoming the intermittent nature of these energy systems. Liquid hydrogen carriers, with their efficiency and storage capacity, are poised to play a central role in this integration, acting as a versatile energy carrier that complements the variable output of renewable sources. As the world shifts towards a renewable energy paradigm, the symbiotic relationship between hydrogen storage and renewables is set to drive transformative changes in how we store, distribute, and utilize energy [18, 20].

4.2 Global trends and policies

On a global scale, emerging trends in hydrogen storage are significantly influenced by international policies and regional dynamics. The impact of international policies on hydrogen storage is profound, with governments worldwide recognizing the strategic importance of hydrogen in their energy transition plans. Supportive policies, incentives, and investments are catalyzing advancements in hydrogen storage technologies, with a particular emphasis on liquid carriers [21, 22]. Regional trends in the adoption of liquid carriers vary based on factors such as energy demand, infrastructure development, and economic priorities. Some regions are witnessing rapid adoption due to a strong emphasis on sustainable energy, while others may be more cautious, weighing factors such as cost and infrastructure readiness. As global collaboration increases and policies align, emerging trends in hydrogen storage, especially with liquid carriers, are poised to drive a transformative shift towards a more sustainable and interconnected energy landscape [21, 23].

5. Challenges and Opportunities

5.1 Identified challenges in adopting liquid hydrogen carriers

As we navigate the landscape of hydrogen storage, the adoption of liquid hydrogen carriers is not without its set of challenges. Foremost among these challenges are the technological hurdles that must be overcome to optimize the efficiency, safety, and scalability of liquid carrier systems [24]. Addressing issues related to hydrogenation and dehydrogenation processes, material compatibility, and the development of robust storage containers are key technological challenges that researchers and engineers are actively working to surmount. The complexities of these challenges underscore the need for sustained research and development efforts to bring liquid carriers to a level of maturity that makes them not only technologically feasible but also commercially viable [19, 21]. Economic considerations pose a significant barrier to the widespread adoption of liquid hydrogen carriers. The infrastructure required for the production, storage, and transportation of liquid carriers demands substantial investment. The cost of materials, energy requirements for the hydrogenation and dehydrogenation processes, and the overall efficiency of the system are critical economic factors that impact the feasibility of liquid carriers on a large scale. Striking a balance between technological advancements and economic viability is a delicate yet essential task that will influence the rate at which liquid carriers become integral components of the hydrogen storage landscape [18, 22, 25].

Regulatory and policy challenges present a multifaceted barrier to the adoption of liquid hydrogen carriers. Existing regulations may not adequately address the unique considerations of liquid carriers, and policy frameworks may lack the necessary incentives to encourage widespread adoption. Balancing safety regulations with the need for innovation and development requires a nuanced approach. Regulatory clarity, along with policies that incentivize the transition to liquid carriers, is essential to creating an environment conducive to their successful integration into the broader energy infrastructure [7].

5.2 Opportunities for further development

Amidst these challenges, there exists a realm of opportunities for further development and growth in the field of liquid hydrogen carriers. One notable opportunity lies in the areas of potential growth and innovation. Continued research and development efforts can unlock new materials, processes, and system designs that address current challenges and push the boundaries of what is achievable. Innovations in catalysts, storage materials, and integration with renewable energy sources represent avenues for growth that could revolutionize the efficiency and practicality of liquid carriers [25, 26].

Collaborative initiatives and partnerships also present significant opportunities. The challenges posed by hydrogen storage are multifaceted, requiring a holistic and collaborative approach. Partnerships between industry players, research institutions, and governments can leverage collective expertise and resources to accelerate the development and adoption of liquid carriers. Collaborative initiatives can facilitate knowledge exchange, streamline regulatory processes, and attract investments that are vital for the continued advancement of liquid hydrogen carrier technologies [9, 27]. In conclusion, the challenges facing the adoption of liquid hydrogen carriers are substantial, spanning technological, economic, and regulatory dimensions. However, these challenges are met with a corresponding set of opportunities that, if seized, can pave the way for transformative growth and innovation in the realm of hydrogen storage. The journey toward widespread adoption of liquid carriers is a dynamic interplay of overcoming hurdles and leveraging opportunities to shape a more sustainable and efficient energy future [9, 12].

6. Conclusion

In summary, the exploration of recent developments and emerging trends in hydrogen storage, particularly in the realm of liquid carriers, reveals a dynamic landscape marked by significant advancements and transformative shifts. Breakthroughs in liquid hydrogen carrier technologies, coupled with their integration with renewable energy sources, stand out as key recent developments. These cutting-edge technologies are reshaping the narrative of hydrogen storage, offering solutions that not only address existing challenges but also pave the way for a sustainable and efficient energy future. The implications of these recent developments are profound for the future of hydrogen storage, especially in the context of liquid carriers. The higher energy density, improved safety features, and potential for easier transportation position liquid carriers as pivotal elements in the evolving hydrogen economy. As the world seeks cleaner and more sustainable energy solutions, the trajectory of hydrogen storage in liquid carriers aligns with the broader goals of decarbonization and energy transition. The implications extend beyond technological advancements, influencing policy frameworks, economic considerations, and global energy landscapes.

As we conclude this exploration of recent developments and emerging trends in hydrogen storage, the vision of a hydrogen-powered future comes into sharper focus. Liquid hydrogen carriers, with their transformative potential, are poised to play a central role in shaping the narrative of sustainable energy storage. The call to action is clear—let us continue to push the boundaries of knowledge, collaborate across disciplines and industries, and collectively drive the evolution of hydrogen storage towards a cleaner, greener, and more resilient energy future.

7. Acknowledgement
The authors acknowledge the Institute of Science, Dr. Homi Bhabha State University, Mumbai, for providing assistance and support for the smooth conduct of the library activities.

8. Declaration of 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. No conflict of interest exists.

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