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Review

A Comprehensive Literature Review on Hydrogen Tanks: Storage, Safety, and Structural Integrity

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Abstract: In recent years, there has been a significant increase in research on hydrogen due to the urgent need to move away from carbon-intensive energy sources. This transition highlights the critical role of hydrogen storage technology, where hydrogen tanks are crucial for achieving cleaner energy solutions. This paper aims to provide a general overview of hydrogen treatment from a mechanical viewpoint, and to create a comprehensive review that integrates the concepts of hydrogen safety and storage. This study explores the potential of hydrogen applications as a clean energy alternative and their role in various sectors, including industry, automotive, aerospace, and marine fields. The review also discusses design technologies, safety measures, material improvements, social impacts, and the regulatory landscape of hydrogen storage tanks and safety technology. This work provides a historical literature review up to 2014 and a systematic literature review from 2014 to the present to fill the gap between hydrogen storage and safety. In particular, a fundamental feature of this work is leveraging systematic procedural techniques for performing an unbiased review study to offer a detailed analysis of contemporary advancements. This innovative approach differs significantly from conventional review methods, since it involves a replicable, scientific, and transparent process, which culminates in minimizing bias and allows for highlighting the fundamental issues about the topics of interest and the main conclusions of the experts in the field of reference. The systematic approach employed in the paper was used to analyze 55 scientific articles, resulting in the identification of six primary categories. The key findings of this review work underline the need for improved materials, enhanced safety protocols, and robust infrastructure to support hydrogen adoption. More importantly, one of the fundamental results of the present review analysis is pinpointing the central role that composite materials will play during the transition toward hydrogen applications based on thin-walled industrial vessels. Future research directions are also proposed in the paper, thereby emphasizing the importance of interdisciplinary collaboration to overcome existing challenges and facilitate the safe and efficient use of hydrogen.

Keywords: hydrogen; hydrogen tanks; hydrogen storage; hydrogen safety; high pressure; low pressure; composite materials; structural integrity; bibliometric analysis

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1. Introduction

1.1. General Background

Hydrogen is currently regarded as a highly promising alternative to fossil fuels for the mitigation of emissions, encompassing both pollutants and agents that contribute to climate change, particularly in applications involving road vehicles and numerous other fields. It can be considered a flexible energy carrier that addresses several essential energy supply and use issues. It is primarily produced from fossil fuels like coal and natural gas, resulting in substantial annual CO_2 emissions, already increasing year after year [1] (Figure 1). In order to facilitate an energy transition, it is imperative that clean hydrogen be made available. The generation of clean hydrogen from renewable or nuclear energy sources or fossil fuels with carbon capture technology has the potential to significantly contribute to reducing carbon emissions across a range of sectors. This encompasses challenging sectors such as long-haul transportation, chemical production, and iron and steel manufacturing, where emission reductions have been challenging to achieve. The introduction of hydrogen-powered vehicles could enhance air quality and contribute to energy security. Furthermore, hydrogen has the potential to facilitate the integration of fluctuating renewable energy sources into the electricity grid, serving as one of the few options for long-term energy storage spanning days, weeks, or months [2,3] .

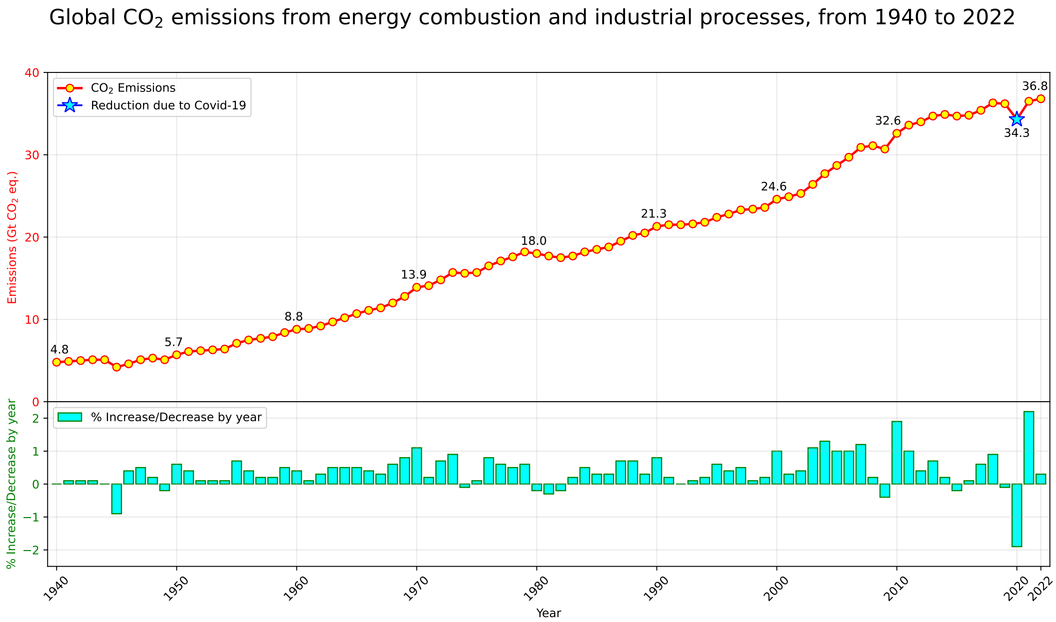

Figure 1. Global CO_2 emissions from energy combustion and industrial processes, from 1940 to 2022. The first plot shows the increasing CO_2 trend, underlining the values (in Gt CO_2 eq.) for every ten years and the last analyzed year (2022), while the second bar chart shows the percentage increase/decrease year by year in (CO_2) emissions. Adapted from [1].

Hydrogen is a promising yet challenging energy carrier due to its unique features. On the positive side, hydrogen boasts an impressive Higher Heating Value (HHV) of approximately 140 MJ/kg, the highest among commonly occurring materials, which makes it an enticing candidate for efficient energy storage and transportation applications. This high energy content means that a relatively small mass of hydrogen can deliver substantial energy output (Table 1). Moreover, this value is roughly three times that of conventional fuels such as gasoline and diesel [4,5]. However, the flip side of this equation is hydrogen's low volumetric density, which poses logistical obstacles. At standard conditions, it has a density of about 0.08988 kg/m^3 (the lowest density of all elements), necessitating large storage volumes for significant quantities of the gas: this makes storing large amounts of hydrogen gas challenging, because it requires more space compared to denser fuels like gasoline or diesel. Despite its volumetric limitations, hydrogen's impressive specific energy underscores its pivotal role in advancing sustainable energy solutions [6].

Table 1. Higher Heating Values (HHV) and Lower Heating Values (LHV) for the most common fuels [7].

Fuel	HHV [MJ/kg]	LHV [MJ/kg]
Hydrogen	141.7	120.0
Methane	55.5	50.0
Butane	49.1	45.3
Gasoline	46.4	43.4
Diesel	45.6	42.6
Methanol	23.0	19.9

1.2. Problem Statement and Formulation of the Research Questions

Throughout history, lots of studies have focused on hydrogen safety and storage. Wurster et al. [8] gave an overview of the potential hazards of hydrogen use in storage systems for different applications: vehicles, trains, aircraft, ships, and stationary applications. The most relevant dangers of using hydrogen are the possibility of explosion, its invisible flames, instantaneous ignition, embrittlement, and its high permeation rate. It has to do with how hydrogen behaves differently from hydrocarbons: it can burn and explode at a broad range, requires little energy to ignite and explode, produces a non-luminous flame, and is highly diffusive and buoyant, which causes flammable clouds to spread quickly. In more detail, Buttner et al. [9] investigated the importance of using sensors to ensure the safe usage of hydrogen and prevent leaks. Kotchourko et al. [10] and Skjold et al. [11] analyzed the problem of explosions that can occur in non-well-ventilated areas. Chen et al. [12] and Wu et al. [13] focused on embrittlement due to the hydrogen–aluminum alloy liner contact. Other significant problems such as ignition (Mueschke et al. [14], Myilsamy et al. [15], Mironov et al. [16]), hydrogen leakage and diffusion (Ishimoto et al. [17], Kobayashi et al. [18], Zhou et al. [19], Sobhaniaragh et al. [20]) have been conducted to deeply understand how hydrogen can be the energy of the future. In this context, it is easy to recognize that hydrogen storage can be a critical technology for successfully commercializing hydrogen-based energy applications. Hydrogen can be stored in various ways, depending on application fields and several other factors [5,21].

For the automotive field, there are two primary ways in which hydrogen can be utilized to produce mechanical energy in a vehicle: Hydrogen Internal Combustion Engine Vehicles (HICEVs) use hydrogen as fuel in a traditional internal combustion engine, while Fuel Cell Electric Vehicles (FCEVs) generate electricity through fuel cells where hydrogen reacts with oxygen, producing water vapor as the only emission [22]. A significant challenge for FCEVs is hydrogen storage due to hydrogen's low density. One method involves Liquid Hydrogen (LH_2) storage, where hydrogen is liquefied at temperatures below 20 K, significantly increasing its density. This method offers high volumetric capacity and lower system costs, but requires high energy for liquefaction and suffers from fuel losses due to boil-off [23,24]. Another method is Gaseous Hydrogen (GH_2) storage, which compresses hydrogen at high pressures (generally 350 bar or 700 bar). This mature technology has low energy consumption, but lower volumetric capacity and higher specific costs, with significant safety concerns due to high pressure [25]. A third method is cryo-compressed hydrogen storage, which combines high pressure and low temperature to enhance density and reduce boil-off [26,27]. While this approach offers high storage capacities and refueling flexibility, it involves high costs and energy consumption [24,25,28]. Using composite materials is fundamental for reducing weight and improving efficiency [29,30], especially in aerospace applications [31–33].

Hydrogen storage technology, particularly in the automotive sector, has made significant advancements over recent years, but several critical challenges remain before widespread commercial adoption can be realized [34]. Current high-pressure hydrogen tanks are relatively mature in design, and have been successfully integrated into fuel cell vehicles such as the Toyota Mirai and Hyundai Nexo [35]. However, several barriers need to be overcome. First, the high cost of hydrogen storage tanks, which are typically constructed from expensive composite materials, remains a significant challenge [24,30]. Reducing the cost of these tanks while maintaining safety and durability standards is essential for widespread adoption [34]. Moreover, the gravimetric and volumetric energy densities of high-pressure hydrogen tanks are still below that of gasoline and gasoil, leading to shorter driving ranges and larger, heavier tanks compared to traditional fuel systems [34,36]. This directly affects vehicle design, requiring space optimization and lightweighting efforts to ensure that hydrogen vehicles remain competitive in terms of range and performance. In addition to cost and energy density, safety concerns surrounding the storage of hydrogen at such high pressures are critical [37,38]. Advances in sensor technologies, leak detection systems, and tank materials are crucial for improving safety, but rigorous testing and certification protocols still need to be standardized across markets [39]. Finally, the refueling infrastructure for hydrogen remains underdeveloped, limiting the practical use of Fuel Cells Vehicles (FCVs) in many regions [34,40].

In aerospace, composite materials, especially Glass Fiber-Reinforced Plastics (GFRP), are crucial for their lightweight and high-temperature resistance [41,42]. GFRP emerged in the 1960s for military and aerospace uses, and later expanded to civilian markets. By 1990, composite tanks for methane at 250 bar were available, evolving to hydrogen storage systems at 700 bar. Key challenges include management, weight, volume, and thermal behavior. Hydrogen, with its high energy content per weight, is advantageous for small military aircraft and long-duration flights. However, water vapor emissions from hydrogen fuel, a potent greenhouse gas, remain a concern [36]. Hydrogen storage in aerospace uses liquid or gaseous forms. LH_2 is favored for its high energy density, though it requires managing heat losses and safety concerns, illustrated by the modified B-57 bomber and Boeing's Phantom Eye UAV. GH_2 storage involves high-pressure cylinders, but faces challenges like material limits, long refueling times, and improved discharge kinetics [36,43]. Historical uses in airships and ongoing advancements highlight the evolution and complexity of hydrogen storage in aerospace [38,42,44].

The incorporation of composite materials, predominantly fiberglass, has markedly enhanced the performance of many maritime vessels, including motorboats, sailboats, catamarans, yachts, and ferries. These materials enhance speed and resistance while simultaneously reducing weight and fuel consumption. Furthermore, hydrogen is emerging as a promising renewable energy source for the maritime sector. Hydrogen fuel cells, which convert hydrogen into electricity, offer a clean energy alternative for the propulsion and powering of ships and onboard systems, with the sole byproduct being water. Despite the considerable advantages offered by hydrogen fuel cells, including high efficiency and low emissions, the widespread adoption of this technology in the maritime industry is hindered by the lack of infrastructure for the production, transportation, and storage of hydrogen. The storage of significant quantities of hydrogen on ships necessitates implementing robust infrastructure and safety measures. The employment of an array of hydrogen storage techniques, including high-pressure, LH_2, metal alloy, and chemical storage, is of paramount importance for ensuring the safety and stability of maritime vessels. The performance and safety of hydrogen storage tanks are influenced by several factors, including the gaseous characteristics of hydrogen, heat generation during release, and external factors such as the stress load on the ship and environmental conditions. These factors have the potential to impact the durability and safety of hydrogen storage systems on boats, thereby necessitating further research to optimize their design and extend their lifespan [45].

1.3. Scopes and Contributions of this Work

Hydrogen has garnered attention since the early 21st century. Figure 2 shows the growing number of scientific papers published on hydrogen tanks related to safety and storage.

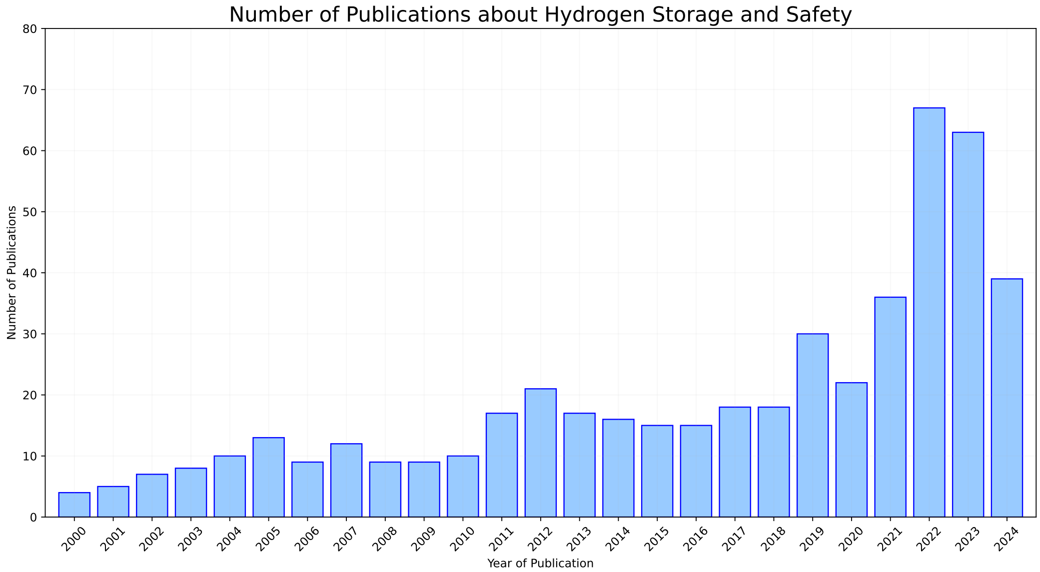

Figure 2. Evolution of published papers about hydrogen tanks (related to safety and storage) recorded in the Scopus database.

Due to the relatively few and pretty general articles available in the literature, a review is necessary to provide a comprehensive and synthesized overview of hydrogen safety and storage by evaluating existing research through a bibliometric analysis. To achieve this, highlighting trends and patterns enables readers to access the most relevant and valuable information on the topic, which is the primary aim of this work [46]. This paper aims to provide a general overview of hydrogen and create a comprehensive review that integrates the concepts of hydrogen safety and storage. As the use of hydrogen energy becomes increasingly central to global sustainability efforts, ensuring the safe and efficient storage of this energy source remains a significant challenge. In this vein, this review work consolidates current research, identifies gaps, and highlights future directions, providing a valuable resource for researchers, engineers, and policymakers. It is particularly relevant for those engaged in energy infrastructure, transportation, and material science and stakeholders involved in regulatory and safety frameworks, which require a comprehensive overview of hydrogen storage technologies and their implications for large-scale implementation. Therefore, this review offers essential insights to a broad audience across academia, industry, and governance sectors. Currently, to the best of the authors' knowledge, this methodological approach has never been used before; in fact, the literature tends to treat these two topics separately, focusing either on hydrogen safety [47] or on storage solutions [48], but not both together. By addressing this gap, the paper will explore the potential of hydrogen as a clean energy alternative and its role in various sectors, including transportation and industrial applications. Moreover, it will highlight the challenges and advancements in hydrogen storage technologies, emphasizing their importance for the successful commercialization and safe implementation of hydrogen-based energy systems. Through this approach, the paper seeks to offer valuable insights into the dual aspects of safety and storage, which are crucial for advancing hydrogen as a sustainable and secure energy carrier. Thus, based on Scopus, a bibliometric analysis was conducted to collect literature reviews and papers and provide a comprehensive assessment of hydrogen safety and storage, ranging from 2014 to 2024.

1.4. Organization of the Manuscript

The paper is organized as follows. Section 1 introduces the topics of primary interest for this investigation. Section 2 describes the type of tanks to give a general idea of how and where the hydrogen can be stored. This classification is provided before the literature review to offer context and clarify the terminology used in this field of investigation. Section 3 gives a historical overview of hydrogen storage and safety development. A narrative approach was used to underline the evolution and implementation of the hydrogen tanks over time. Section 4 describes the methodology used for the systematic literature review, the subsequent bibliometric analysis, and the results obtained from the selected papers. This review process covers the period from 2014 to the present. Section 5 presents a categorized systematization of the analyzed papers. Section 6 summarizes the entire study, and the main directions for future research in hydrogen safety and storage development. Finally, Section 7 presents the conclusions drawn about hydrogen safety and storage tanks.

2. Hydrogen Tanks Classification

2.1. High-Pressure Hydrogen Tanks

The initial technique employed for hydrogen storage was based on the compression of gases. Approximately 140 years ago, the initial hydrogen tanks were developed for military applications. The tanks were constructed entirely of metallic material, specifically steel, and could withstand an operating pressure of 120 bar. In the early sixties, the initial fiberglass composite systems were developed for military and aerospace applications, extending to the civilian market [36]. In approximately the nineties, the initial composite tanks for methane storage at 250 bar were introduced. Subsequently, ongoing research on material optimization and production processes has facilitated the expansion of composite tank technology to hydrogen storage, culminating in the advent of modern systems at 700 bar [23]. As illustrated in Figure 3 and detailed in Table 2, the current classification of high-pressure gas storage tanks is based on the materials utilized and the diverse construction solutions employed in engineering applications. These include the following five types [49–51]:

- Type I: tanks entirely made of metallic material (steel or aluminum) [51,52].
- Type II: Tanks with a main metallic structure, with added circumferential wraps of composite material. They are the evolution of the Type I tanks. The composite reinforcements provide greater strength, allowing a reduction in the thickness of metal walls and, consequently, weight [51,52].
- Type III: Tanks with a predominantly composite structure covering the entire surface. They feature a thin internal metallic layer (steel or aluminum), which provides both structural support and gas impermeability [24,38].
- Type IV: Tanks made of fully composite structure. They include a thin internal layer of polymer material, with the function of preventing gas leakage from the system [24,25,38,53].
- Type V: Tanks entirely made of composite material without any internal coating, characterized by specific resin and fiber orientation choices. This is the most modern storage system, currently reserved for aerospace applications [36,43,50,52].

Table 2. Hydrogen tanks classification and main features [50,51].

Type	Materials			Max. Pressure (bar)	Applications	Structural Load [51]
	Metal	Composite	Polymer			
I	Steel/Al	-	-	Al: 175 Steel: 200	Submarine Applications [54]	Metal body withstands the whole load
II	Steel/Al liner	Filament windings around the cylinder part	-	Al/Glass: 263 Steel/Carbon fiber: 299	Stationary fuel cells and hydrogen (FCH) technologies	Steel and composite materials share the load equally

Table 2. *Cont.*

Type	Materials			Max. Pressure (bar)	Applications	Structural Load [51]
	Metal	Composite	Polymer			
III	Al/Steel liner	Composite over-wrap (fiber glass/ aramid or carbon fiber)	-	Al/Glass: 305 Al/Aramid: 438 Al/Carbon: 700	Vehicles	The composite bears the most load, and the metal liner takes only about 5% mechanical load
IV	-	Composite over-wrap (carbon fiber)	Polymer liner	350 (buses) 700	Vehicles	The composite carries the load
V	-	Composite	-	1000	Aerospace Applications [36,43,55]	The composite carries the load

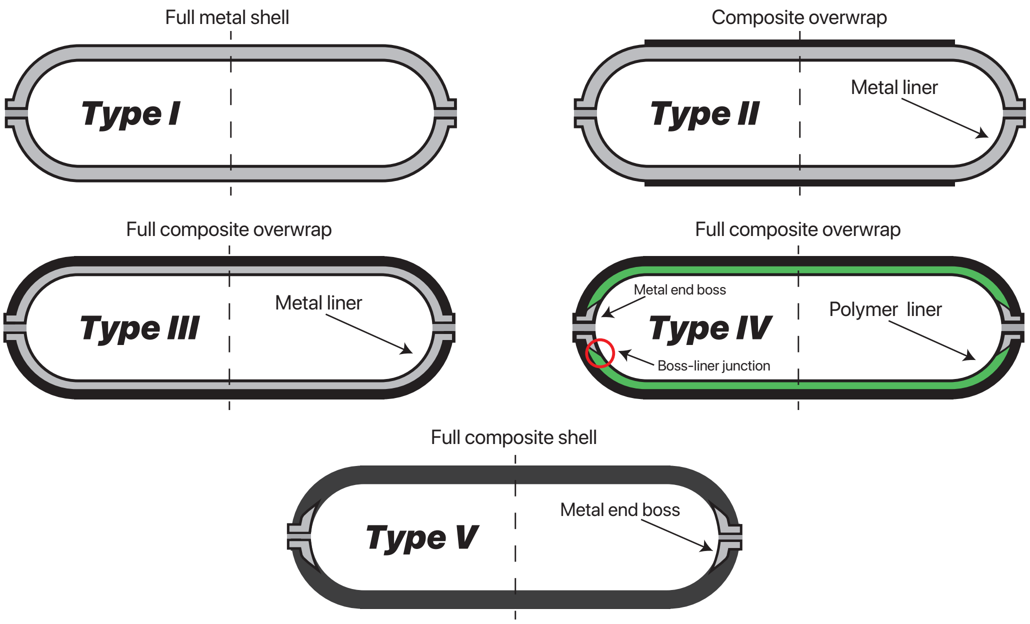

Figure 3. Types of hydrogen tanks and their features. Grey represents the metal part of the tanks; black represents the composite over-wrap; green represents the polymer liner. Adapted from [51].

Type I and Type II tanks feature a low cost. Type III and Type IV tanks, despite higher production costs, are currently adopted by commercial FCEVs due to their superior performance [24,25,38,50]. Type V tanks, reserved for aerospace applications, offer remarkable performance in terms of weight and cost [50,52,55].

2.2. Composite Tanks of Type I

Type I tanks are widely used for hydrogen storage in industrial [49] and submarine applications [54], but their application in fuel cell vehicles is highly disadvantageous. Firstly, they exhibit system gravimetric capacities of less than 0.010 kgH_2/kg_{system}, meaning that to store 5.6 kg of compressed gaseous hydrogen (enough for about 500 km of vehicle range), a storage system weighing 560 kg would be required. Secondly, they have fatigue resistance issues due to hydrogen diffusion into the metal, known as hydrogen embrittlement [23]. The only advantageous aspect of Type I tanks is their lower cost [56].

2.3. Composite Tanks of Type II

Type II tanks use circumferential wraps of unidirectional composite fiber to reduce the required metal mass. From the theory of cylindrical pressure vessels, circumferential stresses are known to be approximately twice those of axial stresses. In the design phase of these systems, the appropriate wall thickness is determined to support the axial pressure load. Then, the amount of composite material to be added is calculated to enable the structure to withstand circumferential stresses. Regarding their gravimetric capacity, Type II tanks represent an intermediate solution between Type I and Type III systems. Although more expensive than Type I tanks, they are less costly than Type III or Type IV systems due to the lower amount of composite material used [50,52]. Type II cylinders are still tested as three large-volume hoop-wrapped composite cylinders with different pressure relief devices (PRDs), focusing on the performance and the rupture disk and rupture disk-fusible alloy assembly devices under fire conditions to optimize their structure and to improve the safety devices [57].

2.4. Composite Tanks of Type III

Type III tanks have an internal metallic shell covered by a thick composite material layer. The internal part (liner) can be aluminum or steel. Its primary function is to make the system impervious to hydrogen leakage and provide structural support, sustaining at least 5% of the internal pressure load. The liner thickness varies depending on the material type, operating pressure, and desired amount of composite material. A higher internal pressure and alloy strength result in a thicker required liner. On the other hand, a thicker composite coating reduces the load percentage on the liner and, consequently, the necessary thickness [58,59]. The threaded valve body connection, linking the storage system to the rest of the equipment, is directly integrated into the top of the liner.

Regarding modern fuel cell vehicle installations, the external structural coating is predominantly made of Carbon Fiber-Reinforced Polymer (CFRP) composite, known for its high stiffness and extraordinary mechanical strength [22]. Alternatively, fiberglass or aramid fibers (Kevlar) could be used, but they would result in an excessively thick structure and; therefore, an overweight tank [60]. This is due to the nature of the materials, generally possessing a lower elastic modulus and, particularly, lower fracture resistance. The carbon fibers are high-strength, with T700 being the most common, offering a good compromise between mechanical strength performance and cost. The typical resin used is epoxy, which is well-suited for the employed production processes and possesses good mechanical properties. Fiber application (roving) usually occurs via the automated filament winding process. After resin impregnation, the fibers are applied to the liner surface with precise orientations until the desired thickness is achieved. A suitable mix of circular wraps, capable of withstanding circumferential stresses, low helix angle wraps (α of about 10°) for axial stress support, and high helix angle wraps (α of about 50°), providing contributions in both directions, is typically utilized [61].

The use of the filament-wound-thin-walled process is the most mature technology for composite pressure vessels to store hydrogen. Still, the critical challenge is accurately examining the mechanical behavior under high pressure and creating advanced models to predict the composite damage [37]. Regarding the composite-hydrogen interaction and behavior, several studies have been conducted, in particular adopting Hydrogen Enhanced Decohesion models (HEDE) [62] and Hydrogen Enhanced Localized Plasticity models (HELP). These two combined models can enhance the development of better and safer composite hydrogen tanks [20].

2.5. Composite Tanks of Type IV

Type IV tanks are similar to Type III tanks, except for the polymer-based liner [63]. Typically, High-Density Polyethylene (HDPE) is used with a thickness of about 5 mm. Alternative materials to HDPE are being studied to offer an increased hydrogen impermeability to reduce liner thickness [42]. Experimental tests demonstrated that PA66 (a type of nylon) can reduce gas leakage through the liner by 92–95% concerning standard HDPE. The main problem is its cost. Indeed, using PA66 could potentially double the manufacturing cost of the whole tank [56]. The liner includes a metallic appendage (boss), needed as a connection element between the tank and the rest of the system (valves, conduits) [50]. The metallic boss is usually made of aluminum alloy 6061-T6, although alternative alloys with better mechanical properties are being evaluated [22]. Similarly to Type III tanks, the external coating of Type IV tanks is CFRP, utilizing the previously mentioned fiber types (T700). Some studies are investigating the possibility of applying other higher-performance, more expensive fiber types as an alternative. For instance, recent optimization studies for high-pressure hydrogen Type IV systems have shown that employing T720 and T800 fibers can reduce tank weight by 6.7% and 10.1%, respectively, concerning the standard T700 configuration. Since the polymer-based liner provides no structural contribution, the composite coating of Type IV tanks is generally thicker than that of Type III tanks (at the same internal pressure and dimensions) [59,64].

Another work introduces a framework combining Machine Learning (ML) with Finite Element (FE) analysis to optimize the design of type IV hydrogen storage vessels rated at 70 MPa. Due to their numerous thin-layer composites and complex dome shapes, the complexity of these vessels makes traditional numerical analysis time-consuming. That is why this approach merges detailed FE models with an Artificial Neural Network (ANN), addressing the irregular material distribution in both cylindrical and dome areas, optimizing the vessel design, and increasing burst pressure from 145 MPa to 157.74 MPa [53].

2.6. Comparison between Type III and Type IV Tanks

To understand the differences and respective advantages of Type III and Type IV tanks, it is helpful to compare their key characteristics directly. Table 3 provides a detailed comparison, highlighting the advantages and disadvantages of Type III and Type IV tanks in terms of weight, system gravimetric capacity, cost, pressure cycle resistance, volumetric capacity, and temperature resistance.

The low hydrogen storage density and self-weight metal liner of the Type III hydrogen tanks make it challenging to achieve the objectives of high efficiency and economy. In contrast, the liner of Type IV hydrogen tanks is made of plastic, which has several benefits, including being lightweight, low cost, long-lasting, and resistant to corrosion and fatigue [50,65].

Table 3. Comparison between Type III and Type IV hydrogen storage tanks.

Feature/Aspect	Type III Tanks	Type IV Tanks
Weight	Heavier (due to metallic liner)	Lighter (due to polymer liner)
System Gravimetric Capacity [22,63]	Lower (due to higher weight)	Higher (due to reduced weight of the polymer liner)
System Cost [63,66]	Higher (because of the cost of the metallic liner)	Lower (despite thicker composite layer)
Pressure Cycle Resistance [22]	Lower (susceptible to hydrogen embrittlement)	Higher (better fatigue life)
System Volumetric Capacity [38,63]	Potentially higher (thinner liners allow more fuel volume)	Lower (due to thicker composite layers)
Temperature Resistance [63]	Better (metallic liner provides significant heat protection)	Lower (polymer liners are less heat-resistant)

This comparison highlights the trade-offs between the two tank types, making determining the most suitable option for specific applications easier, based on their distinct characteristics.

2.7. Composite Tanks of Type V

Type V tanks are the most advanced technology for hydrogen storage. These tanks are made of composite materials to withstand the extreme required pressure. Unlike earlier generations, they have a linerless design, meaning they do not need an internal metal liner, making them more efficient for long-term storage and transportation of hydrogen (Figure 3). They are lightweight, durable, and optimized for high energy density [43,55]. Type V hydrogen-filled tanks are cutting-edge storage solutions currently under development and investigation, and they are still in the research and testing phase, especially in the aerospace field [36,43,67].

3. Historical Perspective

3.1. Section Overview

The concept of storing hydrogen has a long history, with visionaries such as John Dalton among the pioneers. Dalton studied the properties of hydrogen in the 19th century, laying the groundwork for future research into its storage and use as an energy source. Although these concepts did not fully materialize in his time, they laid the foundation for exploring the possibility of safe and efficient hydrogen storage. This section employs a narrative literature review approach to elucidate the evolution of the hydrogen tank concept up to 2014. It is postulated that by observing the temporal evolution of the hydrogen tank idea, the reader can better understand the factual basis that has made hydrogen storage a tangible reality.

3.2. Early 20th Century

The 19th century marked a pivotal era for the understanding and application of hydrogen storage principles, primarily influenced by the groundbreaking work of scientists such as Sir William Grove and Christian Friedrich Schönbein [6,68]. Grove, often credited as the pioneer of fuel cells, laid the groundwork for hydrogen utilization by demonstrating its ability to produce electricity through chemical reactions [69]. Schönbein's discoveries in the 1830s regarding the catalytic decomposition of hydrogen peroxide were pivotal in advancing hydrogen generation and storage methods [70,71]. These early investigations set the stage for subsequent developments in hydrogen storage technologies, as evidenced by subsequent studies cited in the literature [72].

During the early 20th century, the growing interest in hydrogen as a potential energy carrier prompted research into effective storage methods [73]. The works of chemists such as Walther Nernst and Max Bodenstein played a significant role in elucidating the thermodynamic principles governing hydrogen storage [74,75]. Nernst's formulation of the Third Law of Thermodynamics provided invaluable insights into the behavior of gases at low temperatures [76], laying the groundwork for cryogenic hydrogen storage techniques [77]. Bodenstein's studies on gas reactions and kinetics further advanced our understanding of hydrogen storage processes, contributing to the development of high-capacity storage materials [78].

In the following decades, research efforts intensified from the 1920s to the 1930s, focusing on enhancing the efficiency and safety of hydrogen storage systems [79]. Notable advancements during this period include the pioneering work of James Dewar, whose invention of the vacuum flask in 1892 revolutionized cryogenic storage methods [80]. Dewar's innovative approach allowed for the long-term preservation of LH_2 at extremely low temperatures, paving the way for its widespread use in scientific research and industrial applications [23]. Concurrently, researchers explored alternative storage technologies, including metal hydrides and chemical storage compounds, aiming to overcome the limitations of cryogenic storage and facilitate practical hydrogen utilization [81–83].

During the 1940s and 1950s, considerable progress was made in hydrogen storage technologies, driven by the growing demand for hydrogen as a feedstock for various industrial processes and the emergence of applications in the aerospace and energy sectors [84].

Researchers concentrated on optimizing storage materials and systems to meet the evolving needs of a diverse range of end-users [85].

One noteworthy advancement during this period was the refinement of metal hydride-based storage systems [86]. Building upon early experiments conducted by researchers such as Boris Mamyrin and George Olah in the mid-20th century [87,88], scientists and engineers explored novel metal hydride compositions with improved hydrogen storage capacities and kinetics [89]. The capacity of certain metals, such as titanium and magnesium, to form hydrides with high hydrogen uptake capabilities attracted considerable interest, leading to the development of compact and efficient hydrogen storage solutions for portable and stationary applications [90,91].

3.3. Late 20th Century

The late 20th century saw a concerted effort to address the technical challenges hindering the widespread adoption of hydrogen as an energy carrier [49]. During this period, researchers and engineers explored a diverse array of storage technologies, aiming to improve storage capacities, safety, and cost-effectiveness [22,84].

One of the principal areas of focus during the late 20th century was the development of advanced metal hydride storage systems [92]. Metal hydrides offer the potential for high hydrogen storage densities and reversible hydrogen absorption and desorption characteristics [93]. Researchers investigated various metal hydride compositions, including complex hydrides and intermetallic compounds, with the objective of optimizing hydrogen storage performance [94–96]. Significant progress has been made in enhancing the hydrogen absorption kinetics and stability of metal hydride materials, paving the way for their integration into practical storage systems. This has been achieved by developing new materials and improved synthesis techniques, as evidenced by the work of B. Sakintuna et al. [82] and Q. Li et al. [97].

In parallel, advancements in hydrogen compression technologies played a crucial role in expanding the range of viable storage options [92]. High-pressure hydrogen storage tanks became increasingly prevalent, offering a compact and efficient means of storing compressed hydrogen gas [98]. Innovations in compressor design, materials, and control systems enabled the development of lightweight and durable compression units capable of safely storing hydrogen at pressures exceeding 700 bar [98–100]. These advancements were instrumental in supporting the deployment of hydrogen refueling infrastructure for fuel cell vehicles and stationary power applications [101–103]. Furthermore, collaborative initiatives between government agencies, research institutions, and industry stakeholders, such as the Hydrogen Program launched by the United States Department of Energy (DOE) in the late 1970s [63], spurred advancements in compressed hydrogen storage technologies, fostering the commercialization of hydrogen-powered vehicles and stationary energy storage systems [104,105].

Moreover, the advent of nanotechnology in the late 20th century revolutionized hydrogen storage research, offering new avenues for enhancing storage capacities and kinetics. Scientists explored the use of nanomaterials, such as carbon nanotubes, Metal–Organic Frameworks (MOFs), and nanoporous materials, for hydrogen adsorption and storage applications [106,107]. The high surface area and tunable properties of nanomaterials provided unprecedented opportunities for designing lightweight and high-capacity hydrogen storage systems, driving innovation in both academia and industry [108].

Additionally, the late 20th century saw significant efforts to enhance the safety and reliability of hydrogen storage systems. Research initiatives focused on mitigating risks associated with hydrogen handling, storage, and transportation, including developing safety standards and guidelines for hydrogen storage facilities and infrastructure [109]. Collaborative endeavors between government agencies, research institutions, and industry stakeholders facilitated knowledge sharing and technology transfer, accelerating the maturation of hydrogen storage technologies [110].

Overall, the late 20th century represented a period of intensive research and development in hydrogen tank storage, driven by the growing recognition of hydrogen as a clean and versatile energy carrier. The advancements during this period established a foundation for the continued evolution of hydrogen storage technologies in the 21st century, paving the way for the transition toward a hydrogen-based economy.

3.4. From 2000 to 2014

The period from 2000 to 2014 witnessed a remarkable acceleration in the development and commercialization of hydrogen storage technologies, driven by increasing global awareness of the need for clean and sustainable energy solutions [111]. This era saw significant progress in improving the efficiency, safety, and affordability of hydrogen storage systems, paving the way for their widespread deployment in various sectors.

One of the most significant areas of innovation during this period was the optimization of metal hydride storage materials and systems [112]. Building upon the advancements made in the late 20th century, researchers focused on enhancing the hydrogen storage capacities and kinetics of metal hydride alloys, aiming to meet the stringent requirements of automotive and stationary applications [113,114]. Novel alloy compositions and nanostructuring techniques were explored to improve the hydrogen absorption and desorption rates, enabling rapid refueling and extended driving ranges for hydrogen fuel cell vehicles. This was achieved using a combination of novel alloy compositions and nanostructuring techniques, which were explored to improve the hydrogen absorption and desorption rates, enabling rapid refueling and extended driving ranges for hydrogen fuel cell vehicles [95,115].

Simultaneously, advancements in hydrogen compression technologies continued to play a crucial role in enabling practical hydrogen storage solutions. Research efforts were directed towards developing lightweight and efficient compression systems that meet the demanding performance requirements of hydrogen fueling stations and industrial facilities [22,38,116]. The commercialization of high-pressure hydrogen storage tanks with enhanced reliability and cost-effectiveness was made possible by innovations in compressor design, materials, and control algorithms. This was evidenced by the work of J. Jepsen et al. [117], who demonstrated that the reliability of these tanks could be improved by using a combination of advanced materials and control algorithms.

Moreover, the integration of hydrogen storage technologies into emerging energy systems, such as renewable energy storage and grid balancing, gained momentum during this period [118]. Hydrogen-based energy storage solutions, including hydrogen electrolysis coupled with storage in underground caverns or salt domes, offered a scalable and flexible approach to storing excess renewable energy for later use [119]. Research initiatives and pilot projects demonstrated the feasibility and potential benefits of hydrogen storage for enabling the large-scale integration of renewable energy sources into the electricity grid. These benefits include the ability to store excess renewable energy for later use, which is crucial for maintaining a reliable and sustainable energy supply [120,121].

Furthermore, collaborative efforts between government agencies, research institutions, and industry stakeholders played a crucial role in advancing hydrogen storage technologies. These efforts have been instrumental in developing and implementing hydrogen storage solutions that can be integrated into existing energy systems. Public–private partnerships, such as the U.S. Department of Energy's Hydrogen Storage Grand Challenge, which was initiated in 2003 [122], provided funding and support for innovative research projects aimed at overcoming critical technical barriers and accelerating the commercialization of hydrogen storage solutions [105].

In conclusion, between 2000 and 2014, the period of accelerated development and maturation in hydrogen tank storage technologies was driven by technological innovation, industry collaboration, and an increasing market demand for clean energy solutions.

4. Systematic Literature Review Methodology

4.1. Generality

Literature reviews are crucial in offering a comprehensive and contemporary understanding of a specific field, especially in the context of ongoing advancements in scientific and technological research. Researchers often rely on historical reviews and expert opinions to update their knowledge of a topic or issue [123]. This paper initially employs a narrative literature review to explore the historical context of the subjects relevant to this investigation. Subsequently, a systematic literature review is conducted to provide an unbiased and thorough analysis of past and recent developments in hydrogen tank technology development. As explained in [124,125], a significant difference exists between the systematic literature review approach and the narrative method. The systematic literature review approach differs significantly from the narrative method by emphasizing a replicable, scientific, and transparent process [126], which involves comprehensive literature searches to minimize bias and document the reviewers' decisions and conclusions [127]. The methodology used for the systematic review from 2014 onwards, along with a bibliometric analysis, is outlined in this section. Historical literature reviews can be influenced by the reviewer's experience, beliefs, and subjectivity [128], which may impact the selection and representation of evidence, potentially leading to an incomplete representation of current knowledge [124] and introducing sample selection bias. On the other hand, systematic literature reviews employ reliable methods to extract factual and quantitative information, ensuring transparency and scientific rigor [123,124]. This section also describes the standardized approach used to gather, refine, process, and analyze publications on hydrogen tanks, including a bibliometric analysis to quantitatively assess key authors, publications, topics, and research groups.

4.2. Implementation of the Methodology

Following the systematic review approach shown in [3,129], the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard procedure [130] was used to obtain data (Figure 4).

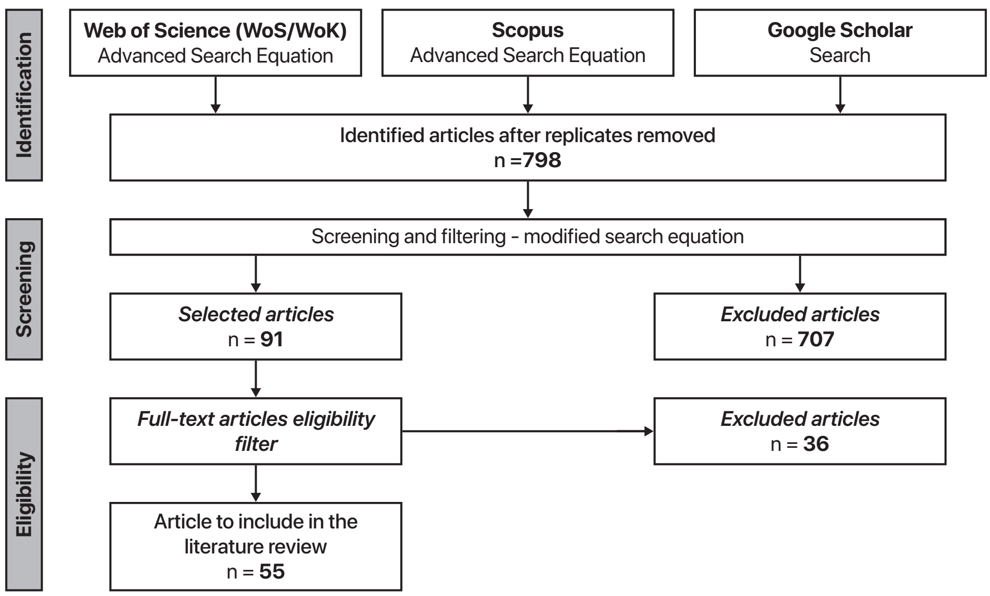

Figure 4. Systematic literature review methodology—PRISMA flow diagram.

Figure 4 shows the systematic procedure used to identify relevant publications from 2014 to the present. This process serves as a framework for reporting systematic reviews. The data input for the Web of Knowledge and Scopus databases involved an advanced search string utilizing Boolean operators, structured as follows:

("Hydrogen tank" AND ("high pressure" OR "low pressure"))

Additionally, a supplementary Google search was performed using the same keywords. Moreover, several keywords were selected in the filter, such as 'Hydrogen Storage', 'Hydrogen Safety', 'Compressed Hydrogen', 'Carbon Fiber Reinforced Plastics', 'Structural Integrity' and 'Composite Materials'. The combined results were then filtered to exclude any documents that were not relevant to the objectives of this review.

4.3. Bibliographic Analysis

The bibliographic analysis of all documents indexed in Web of Science and Scopus was performed using the Bibliometrix tool in R software 4.3.3 [131]. Tables 4–6 present preliminary information on the gathered literature, including details, such as the number of journals, average publication year, average citations per document, and the total number of authors, among other metrics.

Table 4. Main information about the collected document.

Main Information about Data	Results
Timespan	2014: present
Sources (Journals, Books, etc.)	32
Documents	55
Document average age	4.18
Average citations per documents	16.05
References	1792

Table 5. General information on document types and content.

Document Types	Results
Article	32
Conference paper	10
Review	3
Document Contents	**Results**
Keyword plus (ID)	566
Author's keywords (ID)	202

Table 6. General information on authors and author collaboration.

Author	Results
Total authors	185
Authors of single-authored documents	3
Authors Collaboration	**Results**
Single-authored documents	3
Co-Authors per document	4.27

Table 7 presents the most relevant articles selected through the systematic process, while Table 8 highlights the most influential references cited in the documents included in the systematic review.

Table 7. The top 10 most cited document in the review collection.

Most Cited Documents	Total Citations	Total Citations per Year
LI M, 2019, INT J HYDROGEN ENERGY [132]	239	39.83
DE MIGUEL N, 2015, INT J HYDROGEN ENERGY [133]	57	5.70
GOMEZ A, 2019, AEROSP SCI TECHNOL [44]	49	8.17
JOHNSON T, 2015, INT J HYDROGEN ENERGY [134]	47	4.70
MOLKOV V, 2015, INT J HYDROGEN ENERGY [135]	45	4.50
SHEN C, 2018, J LOSS PREV PROCESS IND [136]	44	6.29
GKANAS EI, 2017, RENEW ENERGY [137]	36	4.50
KASHKAROV S, 2020, INT J HYDROGEN [138]	25	5.00
ZHOU C, 2019, J ALLOYS COMPD [139]	23	3.83
CHOI Y, 2022, INT J HYDROGEN ENERGY [140]	21	7.00

Table 8. The 10 most cited references in the review collection.

Most Cited References	Total Citations
MOLKOV, V. ET AL., BLAST WAVE FROM A HIGH-PRESSURE GAS TANK RUPTURE IN A FIRE: STAND-ALONE AND UNDER-VEHICLE HYDROGEN TANKS (2015) [135]	3
ZHANG, Q. ET AL., DESIGN OF A 70 MPA TYPE IV HYDROGEN STORAGE VESSEL USING ACCURATE MODELING TECHNIQUES FOR DOME THICKNESS PREDICTION (2020)[141]	3
BAKER, W.E. ET AL., EXPLOSION HAZARDS AND EVALUATION (1983) [142]	2
BLASSIAU, S. ET AL., MICROMECHANISMS OF LOAD TRANSFER IN A UNIDIRECTIONAL CARBON FIBRE-REINFORCED EPOXY COMPOSITE DUE TO FIBRE FAILURES: PART 3. MULTISCALE RECONSTRUCTION OF COMPOSITE BEHAVIOUR (2008) [143]	2
BOWMAN, R.C., JR., DEVELOPMENT OF METAL HYDRIDE BEDS FOR SORPTION CRYOCOOLERS IN SPACE APPLICATIONS (2003) [144]	2
BRAGIN, M.V. ET AL., PRESSURE LIMIT OF HYDROGEN SPONTANEOUS IGNITION IN A T-SHAPED CHANNEL (2013) [145]	2
DADASHZADEH, M. ET AL., RISK ASSESSMENT METHODOLOGY FOR ONBOARD HYDROGEN STORAGE (2018) [146]	2
DE WAELE, W. ET AL., FEASIBILITY OF INTEGRATED OPTICAL FIBRE SENSORS FOR CONDITION MONITORING OF COMPOSITE STRUCTURES. PART I: COMPARISON OF BRAGG-SENSORS AND STRAIN GAUGES (2003) [147]	2
GOMEZ, A. ET AL., LIQUID HYDROGEN FUEL TANKS FOR COMMERCIAL AVIATION: STRUCTURAL SIZING AND STRESS ANALYSIS (2019) [44]	2
HAN, M.G. ET AL., EVALUATION OF STRUCTURAL INTEGRITY OF TYPE-III HYDROGEN PRESSURE VESSEL UNDER LOW-VELOCITY CAR-TO-CAR COLLISION USING FINITE ELEMENT ANALYSIS (2016) [148]	2

Figure 5 illustrates the scientific output of the top 10 authors during the period covered by this study. The factorial analysis was performed using the Multiple Correspondence Analysis (MCA) technique, employing the keywords of the authors from the selected articles. Figure 5 shows the number of published documents, with the size of the bubbles indicating the quantity. In particular, smaller bubbles represent one publication, while larger bubbles represent two. The color intensity is proportional to the total citations per year. The authors are arranged in descending order of relevance. The relevance of the analysis is assessed based on the number of publications within the specified time frame.

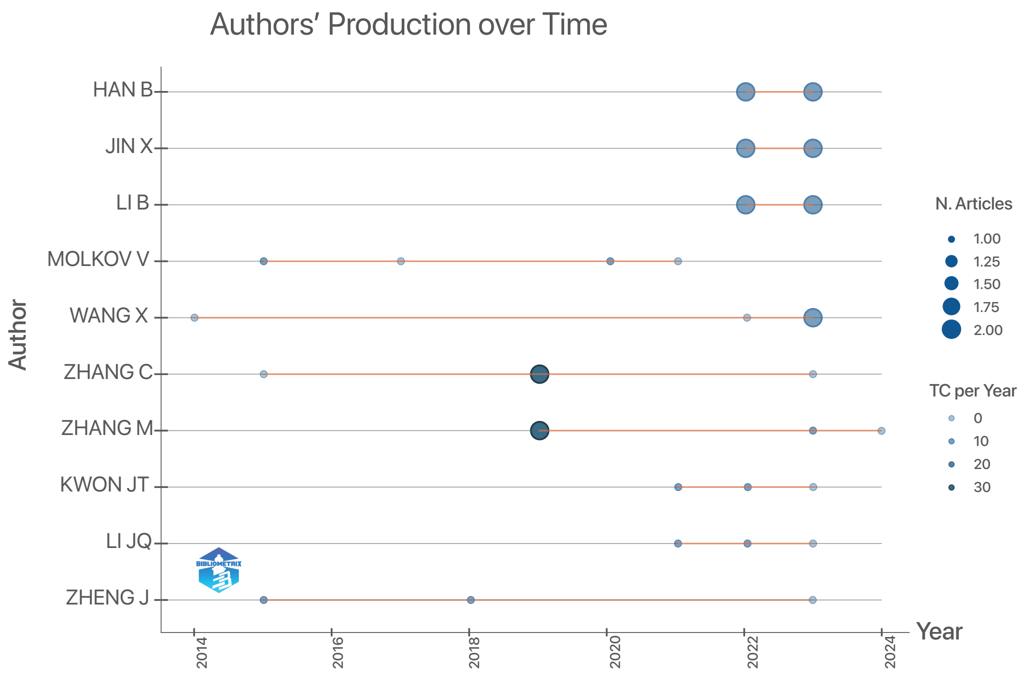

Figure 5. The scientific output of the top ten authors over time. The bubble size represents the number of documents published, with small bubbles indicating one publication and large bubbles indicating two. The color intensity is proportional to the total citations per year.

Figure 6 presents the conceptual structure map of the research topics covered in this work. This figure illustrates the relationships between words based on the proportion of documents that use them as keywords, indicating their similarity [129]. The center of the research field is represented as the origin of the axes, which indicates the average position of all column profiles [129,131]. The percentages on the Dim 1 (43.8%) and Dim 2 (27.34%) axes represent the data variation resulting from dimensionality reduction. The K-means algorithm identified four clusters, each shown in a different color. Purple refers to hydrogen storage tanks and safety technologies; blue denotes the filling related to the temperature rise; green covers fuel cell vehicles design and analysis; and red involves the design of hydrogen vessels.

Figure 7 illustrates the social structure of the researched field through a co-authorship network, highlighting the associations between authors of the systematically collected documents in this review paper. Each author is mentioned using the format "surname + first initial letters of their names". The Kamada–Kawai network layout was used, and normalization was performed using the Salton index, with clustering performed using the Louvain algorithm. The thickness of the edges is proportional to the number of shared works between the connecting authors. The colors indicate the identified clusters of common co-authorship. Figure 7 is helpful to identify influential research groups and authors. In this case, Wang X., Li B., Jin X., Guo C., Han B., and Bi M. are identified as the most influential authors within the analyzed period.

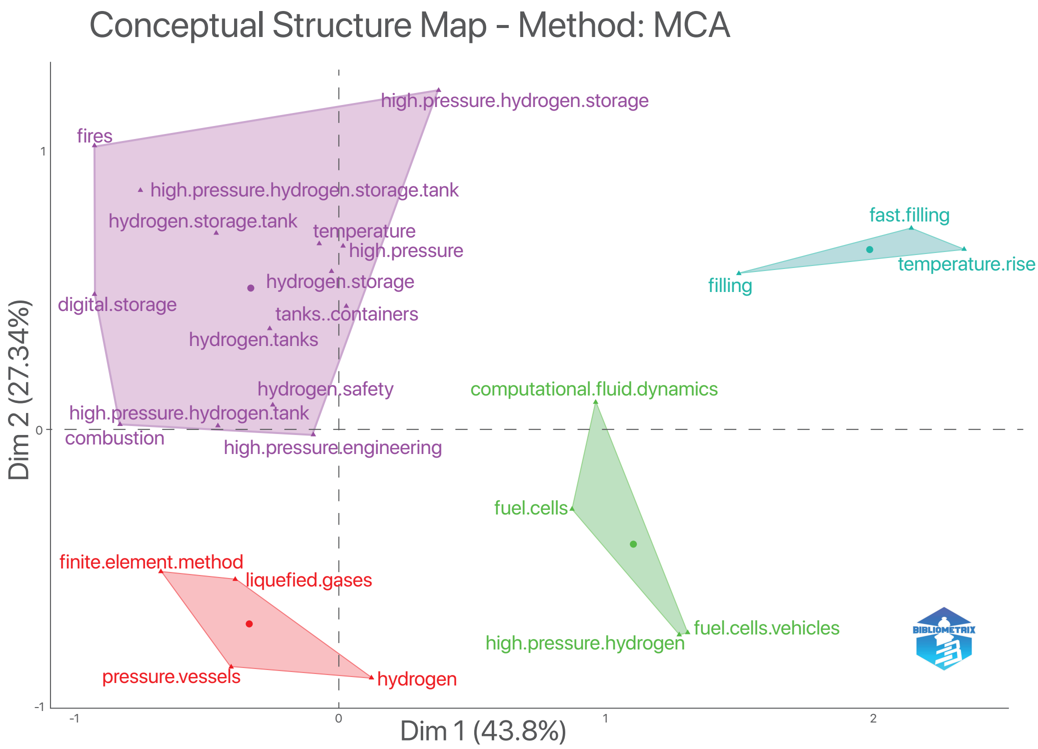

Figure 6. The conceptual structure map created with the MCA algorithm and the K−Means clustering algorithm.

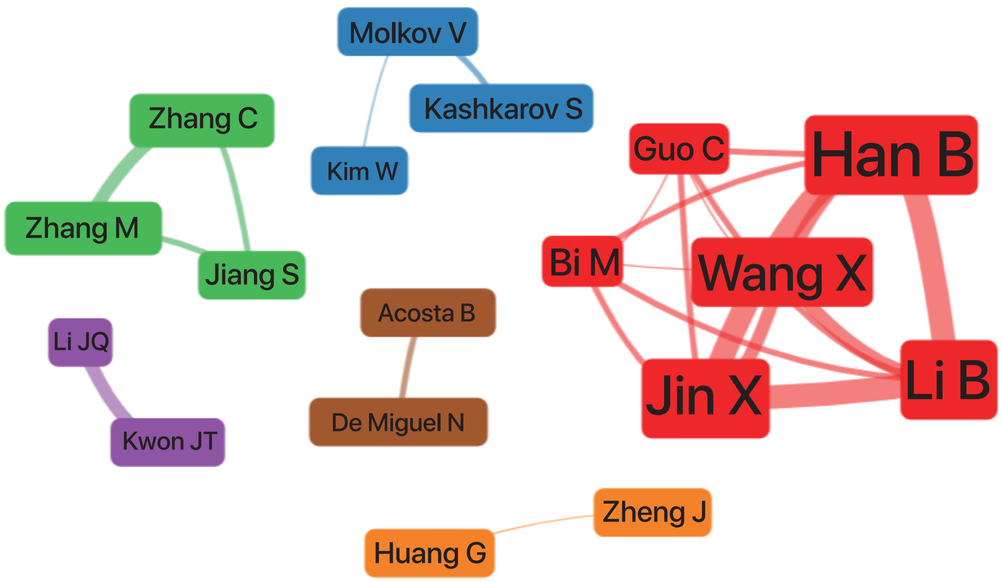

Figure 7. Main authors collaboration network.

Figure 8 shows a word cloud containing the most used word in the papers of the analyzed period. Word clouds are a valuable tool for visualizing text data. They offer several benefits that enhance the understanding and analysis of large volumes of papers. They provide a visually engaging representation, making it easy to identify the most important themes within a dataset. By displaying the frequency of words, they highlight the most commonly used keywords. Word clouds also aid in pattern recognition, revealing relationships between terms that might not be immediately obvious from a traditional text list. More significant words indicate a more substantial presence in the selected articles, so the more critical the characters, the higher the keyword frequency [149]. In the analyzed theme, "tanks (containers)", "hydrogen storage", and "high-pressure hydrogen tank" are the most used keywords.

In summary, the systematic methodology employed in this study facilitated the identification of the most significant research papers in the literature. This process enabled the recognition of the core challenges associated with hydrogen and its storage and safety problems. The subsequent section delves into a detailed discussion of these critical issues.

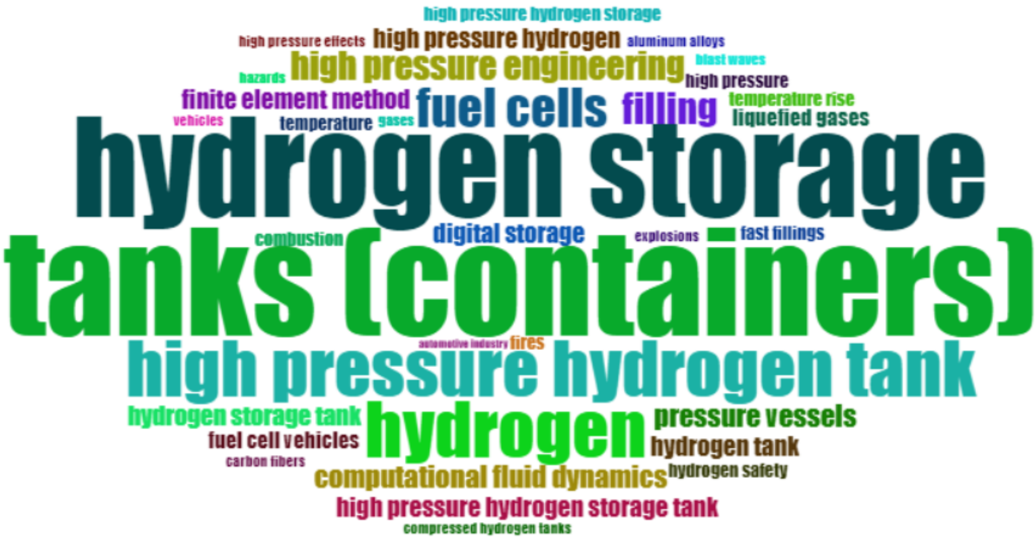

Figure 8. Wordcloud of the most used keywords.

5. Fundamental Issues

5.1. Summary

This section presents a detailed analysis of the primary issues concerning hydrogen storage and safety identified in the previous systematic literature review. A more thorough examination of the gathered papers has been undertaken to achieve this objective. Based on the findings of this review, several research avenues have been identified, and a conceptual map has been generated using the MCA and K-Means clustering algorithms. The primary issues identified through the systematic review and discussed in this paper pertain to the technology of hydrogen tanks, high-pressure hydrogen storage, and safety concerns related to filling and usage.

5.2. Design Technology of Tanks

One of the primary challenges in the design of hydrogen storage tanks is achieving the necessary balance between high storage capacity and safety [8]. Since 2014, significant technological advancements have been made in hydrogen storage tanks. Researchers have focused on improving the efficiency, safety, and storage capacity of these tanks, leading to the development of high-pressure composite tanks and the integration of advanced materials like carbon fiber-reinforced polymers. These innovations have allowed for higher hydrogen storage densities and lighter tanks, making them more suitable for various applications, including automotive and aerospace [35,36]. Despite these advancements, significant challenges remain, such as ensuring the long-term durability and reliability of the tanks under extreme conditions, managing the high costs associated with advanced materials, and addressing safety concerns related to hydrogen's high flammability and potential for leakage. These issues continue to drive ongoing research and development in the field [150,151]. Innovative design solutions can optimize space while maintaining performance standards [53]. Furthermore, manufacturing these tanks at a scale that meets demand while keeping costs manageable is critical, as advanced materials and manufacturing techniques can be expensive. Molkov et al. [135] highlighted the importance of these design considerations in ensuring the safety and effectiveness of hydrogen storage systems.

When designing hydrogen tanks, it ought to take into account the efficient achievement of the required pressure levels (Section 5.2.1), as well as the need for durability (Section 5.2.2) and effective thermal management (Section 5.2.3). Multistage Metal Hydride Hydrogen Compression (MHHC) systems offer a promising solution for achieving high compression ratios within specified temperature ranges. A numerical study on three-stage MHHC cycles revealed the potential to reach compression ratios of up to 22:1, delivering hydrogen at pressures of 315 bar. This underscores the significance of selecting appropriate materials for each compression stage to optimize compression characteristics, minimize energy consumption, and reduce cycle time. However, achieving these goals necessitates ongoing research into materials with improved compression properties, including fast kinetics, low plateau slope, hysteresis, and adequate heat management strategies. Integrating MHHC systems into hydrogen tank design can enhance overall performance and efficiency while meeting stringent pressure requirements for various applications [137].

Jiang et al. [152] proposed an analytical model that integrates the generation of the composite layup and the mechanical evaluation, allowing a rapid and flexible design of the tanks with minimal computational costs. This approach offers a high degree of transparency and ease of implementation, representing a significant advance in designing Type IV hydrogen storage tanks. In more detail, the authors started from the Clairaut equation [153] and focused on geodesic winding paths (Equation (1)).

$$\text{cost} = r \sin(\alpha) \tag{1}$$

where r and α are the cylinder radius and the winding angle, respectively. Because the cylinder radius r does not change on the cylindrical body, the winding angle α remains constant in this region. However, a rapid variation in the winding angle α in the dome region is evident due to the radius reduction. Being symmetrical concerning rotation, the dome can be considered a revolution shell, indicating that the shape is obtained by rotating a curve around the central axis. This curve (the meridian) defines the southern direction. While a cylinder has a straight meridian and has only one curvature, the curved nature of the meridian of the dome introduces a second curvature of the shell. The study is based on the Classical Laminate Theory (CLT), which implies that [154–156]

$$\begin{bmatrix} \mathbf{N} \\ \mathbf{M} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{bmatrix} \boldsymbol{\varepsilon} \\ \boldsymbol{\kappa} \end{bmatrix} \tag{2}$$

where s identifies the meridional direction and θ identifies the circumferential direction. According to Equation (2), the CLT relates the stress-moment resultants $\mathbf{N} = [\mathbf{N}_s, \mathbf{N}_\theta, \mathbf{N}_{s,\theta}]^T$ and $\mathbf{M} = [\mathbf{M}_s, \mathbf{M}_\theta, \mathbf{M}_{s,\theta}]^T$ with strains $\boldsymbol{\varepsilon}$ and curvatures $\boldsymbol{\kappa}$ in their respective directions. The matrices denoted with $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{D}$ are 3×3 stiffness matrices of the composite laminate and can be obtained from the transformed stiffness matrix $\mathbf{Q}$ of single composite layers. The matrix $\mathbf{Q}$, and thus the set of the matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, and $\mathbf{D}$, is strongly dependent on the local winding angle α. The membrane theory provides the first approximate estimation of stress resultants in the s and θ directions. The main assumption of this theory is the neglect of bending effects. The stress resultants obtained in this way are used for the calculations, thereby applying the methodology of Calladine [157]. For a general revolution shell, the membrane theory predicts the following stress resultants:

$$\begin{cases} N_s^* = \dfrac{1}{2} p r_2 \\ N_\theta^* = p\left(r_2 - \dfrac{r_2^2}{2r_1}\right) \end{cases} \tag{3}$$

where the asterisk (*) indicates the ideal nature of the membrane theory, p denotes the pressure of the tank, whereas r_1 and r_2, respectively, represent the two principal radii of the shell [152,157]. For compactness and simplicity, we refer to [152] for more details.

5.2.1. Pressure of Tanks

Tanks designed for high pressure can hold compressed hydrogen gas at up to 700 bar pressure. Furthermore, hydrogen can be cryogenically cooled in insulated tanks to about 20 K at pressures between 6 and 350 bar [158]. In effect, 700 bar and 350 bar hydrogen storage tanks differ primarily in the pressure at which hydrogen is stored, which has significant implications for vehicle design. A 700 bar tank stores hydrogen at a higher pressure, allowing for greater energy density, which translates into longer driving ranges without increasing the tank's size [36,43,98]. This makes 700 bar tanks ideal for passenger vehicles where space is limited. However, the higher pressure requires more robust materials and advanced manufacturing techniques, which can increase the cost and complexity of the tank. On the other hand, 350 bar tanks, commonly used in larger vehicles like buses or trucks, are less expensive to manufacture and maintain, but offer a shorter driving range due to the lower energy density. The choice between 700 bar and 350 bar systems affects vehicle design in terms of weight, cost, and available space for storage, with 700 bar tanks typically favored for light-duty vehicles and 350 bar for heavy-duty applications [159]. Table 9 shows the main different pressure levels properties.

Table 9. Comparison of 350 bar and 700 bar hydrogen storage tanks [36,43,98,159].

Property	700 bar Hydrogen Storage Tank	350 bar Hydrogen Storage Tank
Pressure	700 bar	350 bar
Energy Density (by volume)	Higher (more hydrogen stored per unit volume)	Lower (less hydrogen stored per unit volume)
Storage Temperature	Ambient (−40 °C to 85 °C, depending on conditions)	Ambient (−40 °C to 85 °C, depending on conditions)
Gravimetric Efficiency	Lower (due to stronger, heavier materials needed for high pressure)	Higher (due to lower pressure requirements and lighter materials)
Property	**700 bar Hydrogen Storage Tank**	**350 bar Hydrogen Storage Tank**
Vehicle Range	Longer (more hydrogen stored, better for long-distance travel)	Shorter (less hydrogen stored)
Tank Weight	Heavier (due to stronger tank materials)	Lighter (due to lower pressure requirements)
Applications	Passenger vehicles, small fleets (where space and range are critical)	Buses, trucks, heavy-duty vehicles (where cost is a bigger factor)

Storing hydrogen at very high pressures (up to 700 bar for automotive applications) requires tanks to be designed with structures that can withstand these pressures without compromising safety. Additionally, ensuring that the tanks are lightweight and robust enough to prevent leaks or ruptures is a significant engineering challenge. The complexity of designing tanks that can maintain integrity under extreme conditions, including rapid temperature and mechanical stress changes, further complicates this issue. Another problem is the need for tanks to have a shape and size that can be easily integrated into vehicles or other applications without occupying too much space or adding excessive weight. The work of Ho Nguyen [160] shows an innovative way for automotive applications (designed explicitly for FCEVs) to create a hydrogen tank that respects these conditions. It is a portable hydrogen tank leveraging material-based storage. A three-layer insulation system effectively maintains cryogenic temperatures for over 12 days without external cooling. Operating at pressures below 100 bars and a temperature of 77 K, this tank presents a safer alternative to conventional Type IV tanks operating at 700 bars. By exploiting the

Finite Element Method (FEM) analysis for stress distribution and numerical simulations for heat transfer, the simulation results demonstrate that it is 31% lighter, has an 11% higher capacity, and is 42% cheaper than conventional Type IV hydrogen storage tanks [150]. Stress analysis indicates that the innermost shell endures the highest Von Mises stress, though it remains within safe limits. Integrating conduction and radiation models, heat transfer analysis demonstrates that Multi-Layer Insulation (MLI) effectively minimizes radiation heat ingress [140], allowing for extended storage without cooling.

As highlighted by Cowan et al. [161], the design of hydrogen tanks for FCEVs must respect several essential process design requirements, and different leak, permeation, and pressure cycling tests with high-pressure inert gas and hydrogen must be performed to achieve approval to develop the basis of safety. Through Finite Element Analysis (FEA), the structural behavior of tanks under different loading scenarios, including internal pressure, external forces, and thermal effects, can be obtained, and it is possible to improve efficiency and safety through design optimization [53,150,162,163]. Computational Fluid Dynamics (CFD) software is also employed to support the design of the storage tank, enabling numerical investigations to obtain innovative hydrogen storage tanks [164]. Choi et al. [140] focused on the design strategy and heavy-duty track case study of LH_2 fuel tanks. The study addressed structural design, insulation performance (MLI for insulation), and material selection. The study highlighted economic feasibility challenges for larger tanks and recommended expanded regulations and additional standards to optimize design and installation space efficiency.

Other studies have been carried out on the use of LH_2. Oh et al. [165] dealt with the advantages and challenges of storing and transporting hydrogen in its liquid form (LH_2) as opposed to its high-pressure gas form. The use of LH_2, which can be compressed to a volume 800 times smaller than its gaseous state and has roughly ten times the density of high-pressure hydrogen gas (700 bar), offers significant benefits for storage and transportation efficiency [150]. However, maintaining hydrogen in a liquid state requires advanced insulation to keep the temperature at cryogenic levels (20 K) [165]. Optimization of the design of tanks, pressures, and hydrogen forms, mostly in aerospace fields, is still under investigation [44,150,166].

Due to the three main storage methods (high-pressure gaseous storage, low-temperature liquid storage, and solid-state storage), each has advantages and disadvantages. Additionally, new technologies are currently being studied. High-pressure gaseous storage offers a high energy density, but it is a costly and safety-risky method due to maintaining a high pressure. While LH_2 storage provides an optimal density, it is inherently volatile and requires significant energy input during production. Solid-state storage, utilizing hydride, offers a high level of security and a high volumetric density, although the gravimetric density is comparatively lower. A promising approach is the high-pressure hybrid storage vessel, which combines gaseous and solid-state methods [167].

5.2.2. Durability of Materials

The durability of materials used in hydrogen storage tanks is another critical issue. The high-pressure environment, combined with hydrogen's tendency to embrittle certain metals and alloys, poses significant risks to the long-term integrity of the storage system [13]. Aluminum alloys applied to a liner material of a high-pressure hydrogen tank show several problems [168]. For automotive, but also in aerospace and marine sectors, the usage of Type III and especially Type IV hydrogen tanks instead of Type II is rapidly increasing due to the less presence of metals (Section 2.1).

Composite materials, such as CFRP and GFRP, often address some of these issues due to their strength and lighter weight. However, these materials are also subject to wear and degradation over time, especially when exposed to repeated cycles of pressurization and depressurization. Environmental factors, such as exposure to moisture, extreme temperatures, and UV radiation, can further accelerate the degradation process. Moreover, the interactions between hydrogen and the materials at a microscopic level can develop micro-cracks and other structural weaknesses [20,29,132]. GFRP is rapidly spreading in automotive [135], aerospace [41,42] and aeronautical [45] fields.

Ensuring that materials maintain their strength and integrity over the lifespan of the storage system requires ongoing research and development and rigorous testing under various operating conditions [163]. Zhang et al. [141] emphasized the necessity of accurate modeling techniques to predict material performance and longevity in high-pressure hydrogen storage applications. Temperature-dependent mechanical properties of HDPE used in high-pressure hydrogen storage vessels for automobiles revealed that Young modulus and tensile strengths of HDPE significantly increased with decreasing temperature [169].

Takemoto et al. [170] presented a new method for accurately predicting burst pressures in high-pressure hydrogen tanks made of CFRP for fuel cell vehicles. It focuses on the complex, layered structure of the tanks, which includes carbon fiber bundles and matrix resin. The research utilizes cross-shaped specimens to mimic the conditions of the fiber bundles within the CFRP layers. The results show that the fracture processes of CFRP are significantly influenced by factors such as the strain rate dependency, the tensile-compression asymmetry of the resin, and the strength of the fibers.

Multhoff et al. [171] discussed the limitations and advancements in finite element modeling of Composite Pressure Vessels (CPVs), specifically those created using filament winding techniques. Traditional models based on CLT simplify the composite laminate as a stack of homogeneous plies with consistent thickness, orientation, and mechanical properties. For filament-wound CPVs, each layer is typically represented by two unidirectional plies with opposite fiber angles. However, this simplification does not accurately capture the real fiber geometry, where multiple plies may overlap, and fiber angles vary throughout the laminate. To address this, the research proposes an enhanced filament winding simulation that tracks the deposition of finite-width fiber bands, offering a more detailed representation of the actual fiber paths and overlaps. Transforming this detailed information into a CLT-based finite element model is challenging because it requires a complex mesh layout to represent each ply's unique angles and thicknesses accurately. The ultimate goal is to improve the safe and economical design of high-pressure hydrogen tanks for automotive applications.

Despite their advantages, composite materials represent a big challenge, mainly linked to their thermal response [172,173]. In fact, under fire conditions, the average failure pressure drops to 41.5 MPa, roughly one-third of its burst pressure [172]. This study's results underline that epoxy resin decomposition occurs between 100 °C and 600 °C, with four distinct reaction phases. In comparison, carbon fiber decomposition occurs between 600 °C and 950 °C, with the fastest weight loss rate at 849 °C. Carbon fiber remnants from explosion scenes exhibit brittle, layered breakage, indicating significant mechanical damage. This study also underscores the drastic reduction in tank strength in fire conditions and provides detailed insights into the thermal degradation and damage mechanisms of Type III hydrogen tanks [172]. Similar results were obtained in different studies [174]. In this case, the thermal decomposition behavior of the outer material of high-pressure fully wrapped composite hydrogen storage tanks using a cone calorimeter with piloted ignition at various heat fluxes is investigated. The composite material, consisting of a carbon fiber–epoxy composite covered by a thin layer of glass fiber, was found to follow the thermally thick model. At heat fluxes up to 30 kW/m^2, the carbon fiber–epoxy composite did not ignite. However, at heat fluxes above this value, rapid combustion of the glass fiber and multiple layers of the carbon fiber–epoxy composite is detected.

On the other hand, Benelfellah et al. [175] suggested that applying mechanical load during heat exposure does not significantly alter the thermomechanical properties of the composite material. The temperature distribution, mass loss, and residual tensile strength remained consistent regardless of the mechanical load, mainly due to rapid stress relaxation in the material. This indicates that the performance of the composite material in fire conditions is primarily governed by its thermal properties rather than the additional mechanical stress.

Moreover, developing cost-effective materials that do not compromise performance is challenging. The use of high-performance composites can significantly increase the cost of hydrogen storage solutions, which is a further factor to consider in developing cost-effective solutions [152,176]. Furthermore, reliable monitoring and maintenance strategies must be designed to detect and address material degradation and prevent the failure of hydrogen storage systems. This area requires further research to find innovative solutions [177].

5.2.3. Thermal Performance

Strictly connected to the design and the choice of the material of the tanks (Sections 5.2.1 and 5.2.2), the thermal performance and management are one of the most studied factors about the storage and safety of the high-pressure hydrogen tanks [140,173,174].

One of the most impressive studies was conducted by Wang et al. [178]. The thermal performance of LH_2 storage tanks, particularly in minimizing heat ingress to reduce boil-off gas losses, reveals significant differences between tank designs. Spherical tanks, with a smaller surface area than cylindrical tanks of equal storage volume, experience the slowest pressure increase during self-pressurization due to efficient heat transfer. Horizontal cylindrical tanks exhibit a slower pressure increase than vertical cylindrical tanks because they facilitate more efficient heat transfer between vapor and liquid phases, reducing the temperature difference. As a result, spherical tanks offer the longest holding time, while vertical cylindrical tanks have the shortest, assuming the maximum allowable working pressure remains constant. Higher liquid levels in the tanks contribute to decreased evaporation rates due to the more considerable thermal mass inertia, with evaporation rates following an ascending order from horizontal cylindrical to spherical to vertical cylindrical tanks. Under atmospheric pressure, the temperatures of the vapor and liquid phases maintain stability in a quasi-steady state, and the continuous decrease in liquid level due to evaporation has minimal impact on the evaporation rate. Both horizontal and vertical cylindrical tanks demonstrate similar thermal performance regarding liquid phase temperature, liquid level, and evaporation rate. However, spherical tanks stand out with the lowest evaporation rate due to reduced heat transfer from the environment, with the expansion of the vapor phase volume having a negligible impact on the evaporation rate. The work by Oh et al. [165] on evaporation analysis of LH_2 tank under various heat flow conditions demonstrated that internal pressure increases with higher heat flux rates, and the insulation analysis reveals that decreasing thermal conductivity with reduced vacuum pressure effectively suppresses evaporation and lowers internal pressure. Insulation is still a critical problem while designing hydrogen tanks [150].

Zhou et al. [139] investigated the impact of substituting chromium (Cr) and vanadium (V) into $ZrFe_2$-based alloys on their equilibrium pressure and thermodynamics for hydrogen storage, demonstrating that $ZrFe_2$-based alloys are promising candidates to composite with high pressure compressed hydrogen tanks and thus reduce the working pressure and volume of high-pressure tanks.

Gonin et al. [179] analyzed the safe usage of GH_2 in vehicles using a CFD analysis, demonstrating that tank temperatures must not exceed 85 °C [180] and revealing the potential for vertical thermal stratification during the filling of horizontal tanks.

Mahl et al. [169] provided detailed insights into the temperature-dependent mechanical properties of HDPE used in high-pressure hydrogen storage vessels for automobiles. Experimental investigations revealed that Young modulus and tensile strengths of HDPE significantly increased with decreasing temperature, with Young modulus ranging from 83 N/mm^2 at 373 K to 2381 N/mm^2 at 223 K, and tensile strengths increasing from 4.9 N/mm^2 at 373 K to 40.1 N/mm^2 at 223 K. The compressive to tensile stress ratio exhibited nonlinear behavior depending on temperature and strain range. Finite element simulations using an elastic-plastic model with isotropic hardening and a hyperelastic model demonstrated good agreement with experimental stress–strain data, with minimal relative errors under tensile and compressive loading conditions.

Another critical issue pertaining to thermal management is tank filling. In their research, Li et al. [132] investigated hydrogen storage systems and the development of rapid refueling technology for fuel cell vehicles. High-pressure storage (350 bar or 700 bar) is the preferred option for transportation due to its technical simplicity, reliability, efficiency, and affordability. However, the rapid increase in temperature that occurs during the refueling of high-pressure hydrogen storage cylinders has the potential to reduce the State of Charge (SOC) and cause damage to the tank walls, thereby posing a safety risk. Thermal stress resulting from temperature fluctuations can precipitate the formation of microcracks in resin and composite failure in cylinders. The temperature rise and SOC are influenced by several parameters, including the initial temperature, the type of cylinder, and the initial pressure [181].

Optimal control of initial inlet gas temperature and filling rate is crucial, with precooled hyprecooledlping to reduce initial inlet gas temperature. Coupling cooling temperature and filling rate control can achieve temperature and filling time targets. Numerical simulations based on experimental data verify computational fluid dynamics (CFD). Fast-filling strategies include rate control, refueling with multi-stage pressures, and determining precooling from refueling parameters. Coupling these strategies can create an optimal multi-stage filling strategy to decrease temperature rise and energy consumption [181].

On-board Cold Thermal Energy Storage (CTES) systems, cooled by expanded hydrogen, have been studied to improve energy efficiency and address safety concerns, avoiding significant temperature rise during fast filling, which poses safety risks [164,182]. During the last decade, lots of analysis have been conducted on tanks filling and the related thermal problem, such as fast filling [134,183], rupture during fire tests [136,175], thermal behavior during cycling [40,133], increasing temperature and thermal boundaries [152,184], the correlation with the filling pressure [185,186] and with ultimate pressure-bearing capacity [60].

5.3. Safety and Risks

As described in the previous sections, hydrogen can offer significant environmental benefits, but it also poses unique safety challenges and risks, particularly in storage [47]. Low ignition energy, wide flammability range, and high diffusivity lead to leaks and explosions if not properly managed (Section 1.2). High-pressure hydrogen storage, essential for applications such as FCEVs, increases these risks due to the potential for rapid pressure and temperature changes during refueling [40,132,181,182]. Studies have shown that advanced storage technologies, such as Type III and IV composite cylinders, can mitigate some risks (Section 2). Still, issues like thermal stress and material fatigue remain concerns [135,187]. Additionally, innovations like onboard cold thermal energy storage systems and phase change materials are being explored to enhance safety by managing temperature spikes during hydrogen filling [22,181]. Ensuring hydrogen safety requires a comprehensive approach involving robust engineering solutions, stringent safety standards, and continuous research into material behavior and risk mitigation strategies [188].

5.3.1. Explosions

A significant risk related to hydrogen tank safety is the possibility of explosions [8,16]. Molkov et al. [189] focused on developing and validating a CFD model to simulate the dynamics of blast waves and fireballs following the rupture of high-pressure hydrogen tanks in a fire. The overall goal is to enhance the understanding of the consequences of hydrogen tank rupture and enhance safety engineering and infrastructure development related to hydrogen storage. Improving a previous work on the same wave [135], this study combines experimental data with numerical analysis to gain insights into these phenomena. It finds that the release of chemical energy during combustion significantly affects the blast wave's pressure and impulse. Key findings include the quantitative impact of hydrogen combustion on blast wave strength and the effect of different tank rupture modalities. CFD was also used by Kim et al. [190] in a similar analysis.

On the same topic, explosions and fireballs in a fire environment have been analyzed to develop safety strategies for hydrogen tanks [138]. Wang et al. [191] examined the catastrophic rupture of high-pressure hydrogen storage tanks in fire environments, highlighting the combined physical and chemical explosion hazards. They revealed that fire conditions significantly lower the failure pressure of a 6.8 L–30 MPa tank, causing brief deflagration and giant fireballs. Fragments disperse with high kinetic energy, posing risks over large areas. The study proposes a standardized procedure to evaluate blast wave overpressure and defines risk zones based on experimental data to improve safety for high-pressure hydrogen storage systems. Similar results have been obtained by Li et al. [173] and Makarov et al. [192]. They provide comprehensive insights into the thermal performance and hazard assessment of high-pressure hydrogen storage tanks under fire exposure. Li et al. [173] conducted three bonfire tests on 210 L, 35 MPa composite type III hydrogen tanks to investigate their response in fire scenarios, revealing that failure pressures ranged from 41.1 to 41.8 MPa, with significant reductions in load-bearing capacity under thermal conditions. Their results showed that the Fire Resistance Rating (FRR) varied, with tanks without Thermal Pressure Relief Devices (TPRD) exhibiting longer FRR but decreasing when exposed to engulfing fires before hydrogen blowdown [57,173]. Complementing these findings, Makarov et al. [192] presented engineering correlations for assessing hazard distances defined by fireball sizes following LH_2 spills or high-pressure hydrogen tank ruptures. Their theoretical and experimental analyses provided conservative correlations for fireball sizes, considering factors such as hydrogen mass and fireball geometry. Together, these studies underscore the importance of understanding tank failure mechanisms and fireball dynamics to enhance safety measures and design considerations for hydrogen storage systems.

Additionally, Myilisamy et al. [15] investigated the explosion of a 35-MPa, 72.4 L hydrogen tank at different heights and orientations from the ground, finding that tank height and position significantly affect blast overpressure strength and propagation. Their numerical predictions indicated hydrogen explosions closer to the ground auto-ignite due to the Mach stem phenomenon, which resulted in more hazardous blast effects in the radial direction. The study further concluded that human fatalities could occur up to 2 m from the explosion center, with severe injuries up to 7 m and minor injuries beyond that. Tilting the hydrogen tank increased the potential blast hazards and injuries compared to horizontally placed tanks, highlighting the importance of tank positioning in mitigating explosion risks.

5.3.2. Leakage

The leakage phenomenon in hydrogen storage tanks is a critical issue due to hydrogen's small molecular size, which allows it to permeate through materials and fittings more quickly than larger molecules. This can lead to potential safety hazards, including fire and explosion risks (Section 5.3.1), as well as efficiency losses in storage systems. Understanding and mitigating hydrogen leakage is essential for safely and effectively deploying hydrogen technologies, particularly in high-pressure environments. Ishimoto et al. [17] conducted a comprehensive study on reactive hydrogen leakage from high-pressure tanks, developing an advanced computational method to analyze fluid–structure interactions. This method integrates particle and Eulerian approaches to simulate crack propagation, hydrogen turbulent diffusion, and combustion phenomena. Their findings indicate that combustion reactions are notably absent near the duct center due to excess hydrogen fuel, which increases scalar dissipation. Instead, combustion reactions occur in distinct upper and lower regions as they progress.

Zhou et al. [19] developed a comprehensive model to simulate the leakage process of high-pressure gas storage systems, including tanks and pipes, which can lead to hazardous jet fires and subsequent disastrous events. They built a leakage process model based on the van der Waals equation of state. This model, combined with the notional nozzle and flame size models, predicts gas state properties, flow parameters, and jet flame height during a leakage event. They propose that adiabatic materials should be designed to prevent heat exchange between the tank and its surroundings during leakage experiments, enhancing the model's accuracy and reliability for better isentropic process approximation. This research provides critical insights into the behavior of hydrogen leakage and combustion, emphasizing the importance of precise modeling for the safety and efficiency of high-pressure hydrogen storage systems. Similar studies have been conducted in the aerospace field [44] but also on FCEVs analysis [161].

5.3.3. Embrittlement

The issue of hydrogen embrittlement presents a significant challenge in the development and maintenance of hydrogen storage tanks [8,140]. Hydrogen embrittlement refers to the process by which metals become brittle and fracture due to the permeation and diffusion of hydrogen atoms into the material's structure [23,193]. This phenomenon is particularly critical for high-pressure hydrogen storage systems used in various applications, including FCEVs and industrial storage. Hydrogen embrittlement can compromise the mechanical integrity of storage tanks, leading to catastrophic failures and posing severe safety risks [13]. Recent studies focus on understanding hydrogen embrittlement mechanisms, developing resistant materials, and implementing design strategies to mitigate its effects.

For Type IV hydrogen tanks, a steel boss is used for valve mounting daily, and the hydrogen embrittlement process significantly impacts the steel's performance. Patra et al. [62] focused on the threaded part of 316L stainless steel bosses, essential for fastening valves in 70 MPa compressed hydrogen tanks. They used an analytical approach to understand crack propagation with and without the influence of hydrogen embrittlement. A crack propagation model can be written as below, considering both hydrogen diffusion and $f_{critical}$ [194]:

$$\left(\frac{da}{dN}\right)_{\text{total}} = \left(\frac{da}{dN}\right)_{\text{airfatigue}} + \left(\frac{f_{\text{critical}}}{f}\right)^{\gamma} \left(\frac{da}{dN}\right)_{\text{HAC}}^{\text{max}} \tag{4}$$

In Equation (4), $(\mathrm{da/dN})_{\text{airfatigue}}$ is the Fatigue Crack Growth (FCG) in the presence of air, while $(\mathrm{da/dN})_{\text{HAC}}$ is the FCG due to hydrogen assisted cracking. For the thickness of the polar boss ($\mathrm{h_0}$), two failure conditions have been introduced [62]: the first due to bending moment (Equation (5)), and the second due to transverse shear stress (Equation (6)):

$$h_0 = h(r = r_0) \geq 2.3\, r_f \sqrt{\frac{P}{\sigma_y}\, m_r^o(r_f)} \tag{5}$$

and

$$h_0 \geq \frac{3Pr_o}{4\tau_y} \tag{6}$$

where P is the internal pressure load, σ_y is the material strength, r_f is the largest diameter polar boss, m_r^o is the normalized bending moment. The expression for the axial force acting on the thread is

$$F_{\text{axial}} = \frac{\pi p_w d_t^2}{4} \tag{7}$$

where p_w is the working pressure and d_t is the maximum thread diameter. The shear stresses balance the axial force. It is assumed to be uniformly distributed over the threaded surface of area $\pi \times d_t \times t$, and the shear force acting is

$$F_{\text{thread}} = \pi d_t t \sigma_u \tag{8}$$

where σ_u is the ultimate shear strength and t is the thread engagement length. Giving

$$F_{\text{thread}} = s_f F_{\text{axial}} \tag{9}$$

and putting Equations (7) and (8) into Equation (9), the expression for t is obtained [62]:

$$t = \frac{p_w d_t s_f}{4\sigma_u} \tag{10}$$

After evaluating the combined stress at the thread and the stress intensity factor, the hydrogen embrittlement model has been applied, particularly the HEDE model [20]. We refer to [62] for compactness and any other detailed information. Their results revealed that critical crack length, the threshold at which a crack becomes unstable, increases with the number of loading cycles and, when accounting for hydrogen embrittlement, the critical crack length was 2% to 4% higher, underscoring the increased susceptibility of the material to crack under high-pressure hydrogen conditions. Therefore, considering the effects of hydrogen embrittlement is crucial in designing and maintaining high-pressure hydrogen tanks to ensure their safety and durability. On this line, especially for high-pressure hydrogen tanks for FCEVs, it is essential to explore metallic materials with lightweight properties, high strength, and excellent resistance to hydrogen embrittlement.

In the same context, Owaga et al. [195] conducted a study to evaluate the compatibility of high-strength, precipitation-hardened aluminum alloy 7075-T6. This evaluation involved four types of mechanical testing: slow-strain rate tensile, fatigue life, FCG, and fracture toughness tests in high-pressure GH_2 environments at room temperature. Despite previous reports of significant degradation of 7075-T6 in hydrogenating environments such as moist atmospheres, this study found no degradation in tensile strength and flexibility during slow-strain rate tensile tests in hydrogen gas. The alloy's fatigue life, FCG, and fracture toughness properties were not compromised. These findings suggest that 7075-T6 exhibits excellent resistance to high-pressure GH_2, indicating its potential for use in hydrogen storage tanks for FCEVs.

5.3.4. Autofrettage

This process involves subjecting the inner surface of the tanks to controlled pressure to induce residual compressive stresses, enhancing its resistance to fatigue and stress corrosion cracking. Given the stringent safety requirements of high-pressure hydrogen environments, understanding and optimizing autofrettage techniques are fundamental. The complex distribution of residual stresses induced by welding and autofrettage processes can be examined through numerical modeling. Welding contributes to non-uniform stress distribution along the weld central line and heat-affected zone, posing challenges to structural stability. To mitigate this effect, autofrettage is applied post-welding, resulting in more uniform stress distribution along the tank wall and reduced welding-induced stresses. Consequently, the safety and reliability of high-pressure hydrogen storage tanks are enhanced through the strategic implementation of autofrettage techniques [196].

5.3.5. Advancements in Safety Technologies

Recent advancements in safety protocols and technologies for high-pressure hydrogen tanks have significantly improved safety measures. One notable development is the enhancement of leak detection systems, which now utilize advanced sensors to detect hydrogen concentrations at much lower levels than previous technologies. Qanbar et al. [39] analyze hydrogen sensing technologies and their performances. Commercial hydrogen sensors are primarily electrochemical or catalytic, with significant differences in performance across manufacturers, despite similar designs. Electrochemical sensors are widely used due to their high sensitivity and fast response times, typically detecting hydrogen at concentrations as low as 10 ppm. Catalytic sensors are better suited for detecting combustible gases at lower explosion limits, but may lack specificity for hydrogen detection alone. Resistance-based sensors offer an alternative using solid-state or semiconductive materials, providing robust hydrogen detection with low cross-sensitivity to other gases. The choice of the appropriate sensor depends on the specific application requirements and environmental conditions [39,197].

5.4. Costs and Economic Management

It is of the utmost importance that costs be managed optimally in hydrogen tank technology, as this is a key factor in ensuring the technology's widespread adoption and commercial viability. This entails a comprehensive understanding of various cost factors, including materials [152,160,195], manufacturing processes [151], testing [176,177], overall system costs [63], and safety standards compliance [198]. The economic management of hydrogen tanks involves optimizing these factors to minimize production expenses while ensuring high performance, reliability, and safety [176]. Innovative approaches, such as advanced materials development, automated manufacturing techniques, and streamlined testing procedures, can help to reduce costs without compromising quality or safety. Moreover, leveraging economies of scale through increased production volumes and standardized designs can reduce unit costs [197]. Continuous research and development efforts focused on cost-reduction strategies are essential for making hydrogen tanks more accessible and competitive. By addressing cost challenges effectively, the hydrogen industry can accelerate the transition toward a sustainable and hydrogen-based economy.

5.5. Infrastructure

Building a robust hydrogen safety and storage infrastructure is essential to support the widespread adoption of hydrogen as an energy carrier [138]. This infrastructure encompasses storage facilities, transportation networks, and refueling stations, all of which must adhere to stringent safety standards. Storage facilities range from high-pressure tanks to underground caverns, each with its safety considerations. For example, proper ventilation and leak detection systems are essential in indoor storage facilities to mitigate the risk of hydrogen buildup and potential explosions [135,189] Additionally, the establishment of a dense network of refueling stations is crucial to support the deployment of hydrogen fuel cell vehicles. These stations must have state-of-the-art safety features, including automated shut-off valves and emergency response systems, to protect users and surrounding communities [40,184]. By investing in robust infrastructure and adhering to rigorous safety standards, we can foster public confidence in hydrogen technology and accelerate its integration into our energy landscape [34].

5.6. Social Consideration

In addition to technical considerations, social factors play a significant role in successfully implementing hydrogen safety and storage measures. Public perception of hydrogen as a safe and viable energy source is essential for widespread acceptance and adoption [199]. Therefore, effective communication and education campaigns are crucial to address any misconceptions or concerns surrounding hydrogen technology [200]. Furthermore, community engagement and stakeholder involvement are critical infrastructure planning and deployment aspects. Residents and businesses should have a voice in the siting and design of hydrogen facilities to ensure that their needs and concerns are addressed [2]. Equitable access to hydrogen infrastructure is essential to promote social equity and environmental justice [34]. Efforts should be made to ensure that underserved communities can access clean hydrogen technologies and the associated benefits [63]. By considering social factors alongside technical considerations, we can build a hydrogen infrastructure that is safe, inclusive, and sustainable for all members of society.

5.7. Regulations

Regulation of hydrogen tanks and storage is crucial to ensuring safety and promoting the adoption of hydrogen technologies. These regulations are designed to address the unique risks associated with the high flammability of hydrogen and the high pressures at which it is stored. In the United States, the Department of Transportation (DOT) [201] and the Occupational Safety and Health Administration (OSHA) [202] establish guidelines for the safe handling and transportation of hydrogen. Through its division of Energy Efficiency and Renewable Energy (EERE), the U.S. DOE has been heavily involved in renewable energy research and energy efficiency [122]. The DOE has shown significant interest in developing FCEVs over the past two decades, collaborating with numerous companies and research institutions [63]. A key focus for the DOE is the optimization of hydrogen storage systems, which is critical for the widespread adoption of FCEVs (Table 10). These targets guide research and development efforts to improve hydrogen storage technologies, ensuring they meet stringent safety and efficiency standards. Additionally, the Society of Automotive Engineers (SAE) has established standards like SAE J2601, which provide protocols for hydrogen fueling to ensure safety and performance in hydrogen storage and fuel systems for vehicles [161,179].

Internationally, the International Organization for Standardization (ISO) has developed standards such as ISO 13985 and 19884, which specify requirements for the safety of hydrogen storage systems, both GH_2 and LH_2 [140,198]. All these regulations and standards ensure that hydrogen storage systems are designed, constructed, and operated to minimize risks and protect public safety, thereby facilitating the growth of hydrogen as a clean energy source.

Table 10. Main DOE Targets [203].

Storage Parameter	Units	2020	2025	Ultimate
System Gravimetric Capacity	kWh/kg_{system} kgH_2/kg_{system}	1.5 0.045	1.8 0.055	2.2 0.065
System Volumetric Capacity	$kWh/liter_{system}$ $kgH_2/liter_{system}$	1 0.03	1.3 0.040	1.7 0.050
Storage System Cost	\$/kWh \$/kgH_2	10 333	9 300	8 266

6. Summary and Research Perspective

The general research framework of the authors is built upon three main pillars, each of which is interrelated with the others, concerning hydrogen storage, hydrogen safety, and hydrogen in energy transition [47,48,199]. In this context, this paper presents a literature review on hydrogen storage and safety, especially in the automotive field, but also for industrial, aerospace, and marine applications. An important result of this review investigation is highlighting the pivotal role that composite materials are expected to have in the shift toward hydrogen applications relying on thin-walled pressure vessels.

The number of scientific publications in this sector has increased threefold compared to the preceding decade. Given this exponential growth in this field, the review conducted in this work was divided into two parts. The first part aimed at providing context by unifying documents, articles, and research up to 2014 through a historical literature review. The second part involved a systematic literature review from 2014 to the present to better understand the current research landscape. To achieve this, bibliometric methods were employed to systematically analyze the research field, identifying key documents, references, and authors. Finally, an in-depth analysis of the collected papers was carried out to categorize and determine the current state of hydrogen storage and safety technology development.

To summarize the fundamental outcome of the present study, this review identified three critical issues about hydrogen storage and safety:

- Designing technology of the tanks to ensure the right balance between pressures, materials, and thermal gradients.
- Researching and understanding LH_2 and GH_2 properties to avoid risks such as explosions of the tank, leakage of the hydrogen, material embrittlement, and autofrettage, to improve and guarantee safety.
- Managing costs to encourage the development of this technology and allow hydrogen to become the main form of energy of the future.

Some possible directions for future research are discussed below, together with an assessment of the open main problems. First, there is a need for enhanced materials that can withstand the high pressures and potential embrittlement associated with hydrogen storage [62,161,162]. Research into advanced composite materials and coatings could provide solutions to these challenges [135,170]. Additionally, developing more efficient and cost-effective hydrogen storage systems remains a critical area of focus, as it directly impacts the feasibility of hydrogen as a mainstream energy source. Innovations in storage methods, such as metal hydrides and cryo-compressed hydrogen, offer promising avenues but require further exploration and optimization [24,25,167].

Furthermore, safety protocols and risk mitigation strategies must be continually updated and refined. This includes improving sensor technologies for leak detection and developing more robust containment systems. Collaboration between regulatory bodies and industry stakeholders is essential to establish comprehensive safety standards that keep pace with technological advancements [9,17]. Another critical area is the infrastructure needed to support widespread hydrogen adoption. This involves the physical infrastructure, such as refueling stations and transportation networks, and the regulatory and economic frameworks that will enable the growth of a hydrogen economy. Policymakers and researchers must work together to create incentives and regulations that promote the safe and sustainable use of hydrogen [40,199].

Lastly, public perception and acceptance of hydrogen technologies play a crucial role in their successful implementation. Educational initiatives and transparent communication about the benefits and risks of hydrogen can help build trust and support among consumers and stakeholders. Addressing these open problems through targeted research and collaborative efforts will be pivotal in advancing hydrogen safety and storage, ultimately contributing to a more sustainable and secure energy future.

7. Conclusions

This systematic literature review highlights the critical role of hydrogen storage systems in facilitating the broader adoption of hydrogen as a clean energy source. The review provides an exhaustive examination of the current advancements in hydrogen tank technologies, emphasizing the challenges related to storage efficiency, safety concerns, and structural integrity. The findings indicate that while considerable progress has been made in high-pressure and cryogenic storage methods, there are still significant barriers to overcome, particularly regarding material durability, leak prevention, and cost efficiency. The safety of hydrogen storage remains a primary concern, with advancements in materials science and engineering playing a pivotal role in mitigating the risks associated with pressure containment, fire hazards, and environmental exposure.

The structural integrity of tanks is inextricably linked to the advancement of innovative materials, including composite layers and metal hydrides, which have demonstrated the potential to enhance performance under extreme conditions. Nevertheless, additional research is necessary to optimize these materials for long-term utilization, particularly in harsh operational environments. Furthermore, this review also highlights the necessity for more robust regulatory frameworks and standardized safety protocols to facilitate the extensive implementation of hydrogen storage systems.

In conclusion, this review contributes to the field by providing a comprehensive overview of the current state of hydrogen storage technologies, identifying research gaps, and proposing future research directions that can help bridge these gaps. The insights derived from this review are expected to guide ongoing research and inform industry practices, ultimately supporting the safe and efficient integration of hydrogen energy into global energy systems.

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Abbreviations

The following abbreviations are used in this manuscript:

HHV	Higher Heating Value
LHV	Lower Heating Values
HICEVs	Hydrogen Internal Combustion Engine Vehicles
FCV	Fuel Cells Vehicle
FCEVs	Fuel Cells Electric Vehicles
LH_2	Liquid Hydrogen
GH_2	Gas Hydrogen
GFRP	Glass Fiber-Reinforced Plastics
HEDE	Hydrogen Enhanced Decohesion
HELP	Hydrogen Enhanced Localized Plasticity
PRDs	Pressure Relief Devices
CFRP	Carbon Fiber-Reinforced Polymer
HDPE	High-Density Polyethylene
DOE	Department of Energy
MCA	Multiple Correspondence Analysis
MHHC	Metal Hydride Hydrogen Compression
CFD	Computational Fluid Dynamics
CLT	Classical Laminate Theory
CPVs	Composite Pressure Vessels
SOC	State of Charge
TPRD	Thermal Pressure Relief Devices
FRR	Fire Resistance Rating
FCG	Fatigue Crack Growth

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