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Review Article

Biomass-Derived Functional Silica Materials for Hydrogen Storage: A Short Review

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Abstract

Hydrogen storage remains one of the foremost challenges in the transition to a clean energy economy. While extensive research has focused on metal hydrides, carbon materials, and complex sorbents, biomass-derived silica materials with high purity (90 wt.%), large surface areas (297-895 $m^2.g^{-1}$), and mesopores (3-60 nm) show strong potential for hydrogen storage but remain largely unexplored. This review highlights the synthesis, structural properties, and hydrogen storage potential of biomass-derived functional silica materials, with a particular focus on rice husk (RH) and bamboo as a sustainable and abundant precursor. Two principal silicon extraction strategies, combustion and alkali treatment, are discussed, emphasizing their influence on silica purity, morphology, and amorphous structure retention. Thermochemical processes, including acid leaching and controlled calcination, are shown to be essential for removing impurities and tailoring textural properties such as surface area, pore volume, and pore architecture. RH-derived silica supports exhibit outstanding effectiveness in dispersing transition metals like Ni and Fe, which in turn significantly improve hydrogen sorption kinetics, catalytic efficiency, and the long-term stability of the material. Additionally, the review explores how various synthesis pathways are expected to influence the performance of resulting materials in hydrogen storage systems, noting how structural collapse during reprecipitation or thermal treatment can negate surface advantages if not properly managed. The combined advantages of sustainability, tunable structural properties, and seamless compatibility with existing hydrogen storage strategies position biomass-derived silica as a highly promising next-generation platform for advanced hydrogen storage applications.

Keywords: Biomass-derived silica; Hydrogen storage; Sustainable materials; Rice husk silica; Bamboo

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1. Introduction

Energy plays a vital role in the economic growth and development of all nations. Without it, the production of goods, wealth generation, and future progress would not be possible. In recent decades, global energy demand has significantly increased, with fossil fuels accounting for around 80% of the total energy supply [1]. Fossil fuels such as petroleum, natural gas, and coal have played a major role in powering global progress. However, their widespread use has also significantly contributed to environmental problems, including climate change, global warming, and increased greenhouse gas emissions [2]. Adopting renewable energy and sustainable technologies offers an effective approach to tackling energy shortages, cutting carbon emissions, lessening the greenhouse effect, and addressing various global challenges [3–5]. Renewable energy provides a range of benefits,

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including being environmentally friendly, dependable, safe, and widely available [6]. Hydrogen energy stands out as a clean and sustainable option among renewable sources. With a higher energy density than traditional fossil fuels such as gasoline, it is increasingly viewed as a promising alternative fuel [7]. Moreover, the rising cost and limited availability of conventional fuels, especially gasoline, highlight the need for alternatives. In this context, hydrogen emerges as a promising substitute for fossil fuels [8]. However, to use hydrogen efficiently as a transportation fuel, it is crucial to achieve safe storage with high capacity and density [9]. Hydrogen's transport, storage, and safety continue to be key areas of active research and technological advancement [10,11].

At present, hydrogen can be stored using three primary methods, such as a compressed gas, in liquid form at low temperatures, or within solid materials [12]. Storing hydrogen as a high-pressure gas, typically at 35 to 70 MPa, is the most widely used method. However, its low volumetric energy density limits overall efficiency [13]. Materials used for this method need to be both strong enough to withstand high pressure and lightweight, which increases costs and complicates maintenance, thereby limiting its widespread use [14]. On the other hand, storing hydrogen as a liquid at low temperatures reaches a density of about 70 kg/m^3 at atmospheric pressure. However, the liquefaction process demands substantial energy, around 30 to 40% of the hydrogen's total energy content and requires storage tanks to be highly insulated and airtight [15]. As a result, liquid hydrogen storage is primarily employed in sectors like the military, aviation, and aerospace, where high costs are more acceptable [16].

Solid-state storage systems can hold greater amounts of hydrogen within a given volume compared to gas or liquid storage, primarily by utilizing physical adsorption and chemical absorption mechanisms [17]. In physical adsorption, hydrogen is held within microporous and tubular frameworks, whereas chemical absorption involves forming stable hydrides through reactions with elemental, intermetallic, or complex compounds [16,17]. However, the chemical absorption approach encounters difficulties, including elevated temperatures needed for hydrogen release, sluggish reaction rates, possible irreversible changes, and high costs [18]. Compared to other techniques, the physical adsorption method offers several benefits, such as rapid reaction rates, high hydrogen storage capacity by volume and weight, excellent reversibility and cycling stability, as well as being lightweight and cost-effective [19,20]. This approach uses porous materials, with silica-based porous materials (PSMs) and their composites standing out as especially promising options for hydrogen storage compared to other alternatives [9]. This advantage stems from their easy synthesis processes and outstanding features, including a large specific surface area and well-developed pore structures [21–23]. PSMs play a crucial role in many applications and can be produced from a variety of sources, including biomass like rice husk and sugarcane bagasse [24,25], industrial waste materials (e.g., fly ash, silica fume) [26,27], and synthetic precursors (e.g., tetraethyl orthosilicate [TEOS], sodium silicate) [28,29]. Biomass waste-derived PSMs represent a promising direction for advancing hydrogen storage technologies. Utilizing global biomass in this way not only supports various applications but also helps reduce environmental impact by turning waste into a valuable resource [30].

Numerous reviews have covered the use of porous materials in energy storage [11,30–34]. However, few, if any, have specifically examined and compared biomass-derived porous silica materials and their composites for hydrogen storage. This review was conducted through a critical analysis of peer-reviewed journal articles sourced from major scientific databases, including Scopus and Web of Science (WoS). The literature spans from the early 2000s to 2025, encompassing both seminal studies that established the fundamentals of hydrogen storage and biomass-derived silica materials, as well as recent advances reported in the literature. The primary goal of this review is to systematically evaluate the potential of biomass-derived functional silica materials as sustainable scaffolds for hydrogen storage systems, with particular emphasis on structure-property-performance relationships, processing challenges, and future research directions.

2. The Switch-Over to Biomass-Derived Functional Silica Materials in Hydrogen Storage Applications

Biomass, originally used for direct combustion as an energy source, has increasingly gained attention for its potential to be transformed into high-value functional materials through chemical, biochemical, and thermochemical methods [32,35]. As a sustainable and abundant resource, biomass offers a compelling pathway for producing materials such as silica, which holds promise for hydrogen energy storage applications [36].

In recent decades, there has been growing research interest in extracting silica from natural materials because of its low cost, eco-friendliness, and wide availability [35]. Common sources of silica precursors include rice husk [36], corn cob [37], bamboo leaf [38], sugarcane bagasse [39], and coconut husk [40]. Unlike synthetic mesoporous silicas, biomass-derived silica can be produced using low-cost precursors, mild processing conditions, and minimal environmental impact [41]. Moreover, the natural structure and composition of biogenic silica precursors often yield porous frameworks with high surface area, tunable pore size distribution, and improved thermal stability, all of which are advantageous for hydrogen adsorption and desorption [42]. Beyond these macroscopic advantages, the effectiveness of biomass-derived silica for hydrogen storage is fundamentally governed by molecular-scale surface-hydrogen interactions.

From a molecular perspective, the suitability of biomass-derived functional silica for hydrogen storage arises from its surface chemistry, structural disorder, and pore-molecule interactions. Biogenic silica typically contains a high density of surface silanol (≡Si–OH) groups, which introduce polar adsorption sites capable of interacting with hydrogen molecules through weak quadrupole–dipole and van der Waals forces [43,44]. In addition, biomass-derived silica often exhibits an amorphous and defect-rich framework, generating localized adsorption potential wells that further promote hydrogen uptake without compromising reversibility [45].

The naturally inherited hierarchical porosity of biogenic silica, encompassing micro- and mesoporous domains, is particularly advantageous at the molecular scale, as pore dimensions approaching the kinetic diameter of hydrogen molecules induce confinement effects that increase adsorption strength [8,46]. Furthermore, the abundance of surface hydroxyl groups facilitates the uniform dispersion and anchoring of catalytically active metal species, enabling hydrogen spillover mechanisms in which molecular hydrogen dissociates on metal sites and migrates onto the silica surface [47,48]. Collectively, these molecular-scale features distinguish biomass-derived functional silica from conventional synthetic analogues and underpin its growing relevance in hydrogen storage applications.

The shift toward biomass-derived functional silica materials is also driven by the limitations of traditional (non-biomass) materials used in hydrogen storage. Although extensive research on metal-organic frameworks (MOFs) [49], zeolites [50] and covalent-organic frameworks (COFs) [51], carbon-based materials such as carbon nanotubes (CNTs) [52], activated carbons (ACs) [53], carbon nanofibers (CNFs) [54], graphene [55], and synthetic mesoporous silicas [22] has provided benchmarks in storage capacity, kinetics, and thermal stability, these materials often suffer from complex synthesis, high production costs, and limited scalability [2,19,56]. Insights from these non-biomass materials, however, remain valuable; they help identify challenges such as thermal degradation, sluggish kinetics, and structural instability that must also be addressed in biomass-based systems.

Importantly, biomass-derived silica materials not only address the economic and environmental drawbacks of conventional materials but also support global sustainability goals. The utilization of agricultural waste contributes to waste valorization, reduces landfill burden, and promotes a circular bioeconomy [57,58]. According to projections, biomass-based energy systems are expected to meet 40% of the world's renewable energy demand within the next decade [59]. Furthermore, the use of biomass-based silica for hydrogen storage aligns with efforts to develop decentralized, portable energy storage systems, especially in regions facing energy poverty or lacking infrastructure [60].

In this context, the development of functional silica materials from biomass offers a dual advantage: environmental remediation through waste management and the fabrication of promising materials for clean energy applications [32]. As the demand for high-density hydrogen storage materials grows, the exploration and optimization of biomass-derived porous silica structures will be crucial. These materials can not only meet the performance expectations established by synthetic analogues but also exceed them in terms of sustainability and cost-effectiveness.

3. Molecular Mechanisms of Hydrogen Adsorption and Storage in Porous Materials

Hydrogen storage in porous materials, such as silica-based, carbon-based, and metal-doped frameworks, is fundamentally governed by molecular-scale interactions between hydrogen molecules and the host material. These interactions can be broadly classified into physisorption, chemisorption, and spillover mechanisms, each influenced by the surface chemistry, porosity, and functionalization of the support material [9,61].

3.1. Physisorption Mechanism

Physisorption, or physical adsorption, is the most common mechanism in porous silica and carbon materials. Hydrogen molecules interact with the surface primarily through van der Waals forces and quadrupole-dipole interactions with polar functional groups, such as silanol (≡Si-OH) groups on silica or defect sites on carbon surfaces [62,63]. The pore structure plays a critical role in enhancing adsorption. Micropores (<2 nm) provide confinement effects that increase the adsorption potential of hydrogen molecules, whereas mesopores (2–50 nm) facilitate rapid diffusion and accessibility of active sites [7,8].

3.2. Hydrogen Spillover Mechanism

In metal-doped porous supports, such as iron (Fe), nickel (Ni), or platinum (Pt), which are well-known hydrogen-active metals, functionalized silica or carbon, hydrogen adsorption can occur via spillover [12,64]. In this process, molecular hydrogen first dissociates on the metal nanoparticles into atomic hydrogen, which then migrates onto the support surface, enabling storage beyond the intrinsic physisorption limit [65]. The efficiency of spillover depends on the metal dispersion, metal-support interaction, and surface functional groups that facilitate hydrogen migration [66]. Surface hydroxyl groups on silica and defects on carbon act as anchoring sites for both the metal and atomic hydrogen, stabilizing the adsorbed species [67,68].

3.3. Chemisorption and Hydride Formation

Although chemisorption is less common in pure silica or carbon, it becomes relevant in metal hydride or metal-doped systems, such as magnesium hydride (MgH_2) confined in silica [69]. In these systems, hydrogen forms stronger chemical bonds with metal atoms, enabling higher storage densities, but typically at the expense of higher desorption temperatures and slower kinetics [70,71]. Confined systems benefit from reduced particle size and enhanced surface contact, which lowers activation barriers for hydrogen uptake and release [72].

3.4. Hydrogen Desorption and Release Mechanisms

Hydrogen desorption in porous silica-based and composite storage systems is governed by the reversibility of the underlying adsorption mechanisms and the accessibility of diffusion pathways within the host material [73]. In physisorption-dominated systems, hydrogen molecules are weakly bound through van der Waals and quadrupole-dipole interactions, allowing rapid and fully reversible desorption upon modest changes in temperature or pressure [62,63]. The open and interconnected pore networks characteristic of porous silica facilitate efficient hydrogen diffusion during both adsorption and release, minimizing the risk of permanent molecular entrapment [9].

In spillover-based systems, hydrogen desorption occurs through the recombination of surface-migrated atomic hydrogen into molecular hydrogen, followed by diffusion out of the porous matrix. This process is strongly influenced by metal–support interactions and surface functional groups, which regulate hydrogen mobility without forming irreversible bonds [74]. For chemisorption-based storage, such as metal hydrides confined within silica scaffolds, hydrogen release is primarily controlled by the thermodynamics and kinetics of the active hydride phase [69]. In these cases, the silica framework functions as a structural stabilizer and diffusion medium rather than a hydrogen-trapping material, contributing to reduced diffusion lengths and improved reversibility [70]. Overall, effective hydrogen release in biomass-derived functional silica systems relies on balancing adsorption strength with pore accessibility and surface chemistry, ensuring reversible storage suitable for practical applications.

4. Biomass-Derived Functional Silica Material

The utilization of biomass as an economical silicon (Si) source is attractive due to the unique biogenic morphology and inherent structural features of Si in plant-based materials [33]. Among the various biomass-derived options, rice husk (RH) is considered the most feasible and widely used precursor, primarily owing to its high silica content (~20 wt.%) and global abundance [75,76]. Although other agricultural residues such as rice straw, corn cobs, and sugarcane bagasse have also been investigated, RH remains the dominant choice due to its superior silica content and favorable processing characteristics. Notably, RH and its derivatives are often referred to as a “bio-silica reservoir,” as the silica taken up from the soil by paddy plants accumulates predominantly in the husk in the form of hydrated amorphous SiO_2 spheres [77]. RH, an abundantly available agricultural byproduct, is commonly disposed off through incineration or landfilling, yet its transformation into functional materials remains largely underutilized at the industrial scale. Through direct thermal treatment, RH can be converted into rice husk ash (RHA) containing up to 90 wt.% SiO_2 after the removal of organic volatiles [78,79]. Additional purification via acid leaching and alkaline treatment can raise the silica purity to 99.8% [80].

While RH-derived silica has been studied for various applications, its potential in hydrogen storage systems is still underexplored, despite its favorable physicochemical properties and sustainability as a feedstock. Currently, biomass-derived silica-based materials have been successfully applied in a variety of fields, including catalytic degradation [81], adsorption [82], biosensing [83], supercapacitors [84], and drug delivery systems [85], among others. Figure 1 illustrates the diverse applications of silica. As evident from Figure 1 (a), biomass-derived functional silica material is predominantly utilized in energy-related applications, underscoring its potential as a functional material in emerging clean energy technologies. This section covers the extraction of silicon from biomass, the techniques used to prepare silica-based materials, and the impact of process parameters on their physical and chemical characteristics.

4.1. Preparation of Biomass-Derived Functional Silica Materials

Biomass-derived silica can be tailored with specific structural or chemical features, such as high surface area, porosity, or surface functional groups, that make it suitable for targeted applications such as catalysis, adsorption, and hydrogen storage [86]. These tailored materials are referred to as functional silica materials. Before producing such materials from biomass, silicon must first be extracted. The main extraction techniques are combustion and alkali treatment. Combustion involves burning the biomass to eliminate organic components, leaving behind crystalline or amorphous silicon dioxide (SiO_2). In the alkali treatment process, biomass is initially pyrolyzed at temperatures between 400 and 700 °C to generate biochar. Silica is then leached from the biochar using an alkaline solution to form sodium silicate, which can either be concentrated into a sodium silicate solution or calcined to yield SiO_2 [31]. The detailed procedure is illustrated in Figure 1 (b). As shown in Figure 1 (b), combustion is the simplest and most widely used technique for extracting high-purity silicon from biomass. To improve silica purity, the biomass is often pretreated with acidic solutions to eliminate metal contaminants [87]. Sulfuric acid (H_2SO_4) and hydrochloric acid (HCl) are the acids most frequently used for treating biomass. In this process, the biomass is initially soaked in an acidic solution and stirred under controlled temperature and pressure for a designated time. Afterward, it is filtered or centrifuged to separate impurities. The treated biomass is then calcined to burn off organic material, leaving behind inorganic SiO_2 [88]. For instance, Madduluri *et al.* [89] successfully removed iron (Fe), manganese (Mn), potassium (K), and other metallic impurities from rice husk using HCl acid leaching, followed by calcination at 600 °C to obtain high-purity SiO_2.

Similarly, Denise *et al.* [90] employed citric acid to extract earth alkali ions from rice husks, achieving silica with a purity of 99.7 wt.% after calcination at temperatures above 600 °C. According to Sprynskyy *et al.* [91], thermal treatment of biosilica proceeds through three main stages: dehydration (30-112 °C), initial dehydroxylation and decomposition of organics (199-576 °C), and further dehydroxylation (576-806 °C), which removes internal hydroxyl groups from the silica network. These transformations are crucial, as the calcination temperature significantly affects the final structure of the silica. Notably, amorphous SiO_2, which is preferable for developing mesoporous silica materials, typically forms at 500-800 °C, while temperatures exceeding 900 °C led to crystalline phases that are less suitable for porous material synthesis [92].

As illustrated in Figure 1(b), the alkali treatment involves using alkaline agents like sodium hydroxide (NaOH) to etch biochar. The alkali penetrates the biochar and reacts with SiO_2, transforming it into soluble silicate. This process can be done by either mixing biochar directly with the alkali and heating it or by soaking the biochar in an alkaline solution, drying, heating, and then washing it with water to dissolve the silicate. Gong *et al.* [93] carbonized ground straw at 800 °C to produce biochar, which was then treated with a NaOH solution to extract sodium silicate. This silicate was later used as a precursor for synthesizing mesoporous silica. Alternatively, the extracted silicate can be reacted with an acid to form silica gel through the sol-gel process. Sugarcane bagasse has also been used to extract silica due to its abundance, low cost, and relatively high silica content [94]. For instance, Norsuraya *et al.* [25] first calcined sugarcane bagasse to obtain ash, which was then treated with hydrochloric acid to eliminate aluminum and iron impurities. The purified ash was subsequently soaked in a NaOH solution to extract sodium silicate, which served as the silicon source for synthesizing mesoporous silica. The extracted silica can achieve a purity of up to 88.13%. The underlying mechanism of this extraction process is outlined in Equation (1) and Equation (2) [95].

$$SiO_2 + 2OH^- \rightarrow SiO_3^{2-} + H_2O \tag{1}$$

$$SiO_3^{2-} + 2H^+ \rightarrow SiO_2 + H_2O \tag{2}$$

Therefore, controlled thermal and chemical treatments not only ensure high-purity silica but also preserve its amorphous and porous nature, features that are highly favorable for hydrogen storage applications. Amorphous biosilica offers a large surface area, tunable pore size, and reactive silanol groups, making it a promising support material for hosting hydrides or metal catalysts in hydrogen storage systems.

Currently, RH is widely utilized as a precursor for developing catalyst supports due to its amorphous structure, which promotes a large surface-area-to-volume ratio. Notably, Chun *et al.* [80] synthesized high-purity mesoporous silica (up to 99.8%) from RH through a multi-step process: acid treatment to remove inorganic impurities, combustion to eliminate organic matter, alkaline extraction to isolate silicon, and reprecipitation to form SiO_2. As shown in Figure 2 (a), the resulting SiO_2 exhibited irregular morphology due to uncontrolled precipitation. However, by introducing appropriate surfactants during the precipitation step, the morphology and pore architecture of the final product can be finely tuned, yielding mesoporous structures such as nanochannels or mesocellular forms with pore diameters ranging from 3-60 nm and pore volumes between 0.81-1.77 $cm^3.g^{-1}$. The resulting materials also demonstrated high surface areas (297-895 $m^2.g^{-1}$), characteristics that are highly desirable for hydrogen storage applications, where tailored porosity and high surface area are crucial for enhancing adsorption and improving kinetics. These findings underscore the untapped potential of RH-derived silica as a sustainable and cost-effective functional material in hydrogen storage systems.

Madduluri *et al.* [89] investigated the catalytic performance of Ni supported on RH-derived carbon–silica (C–SiO_2) for the hydrogenation of furfural and levulinic acid. The C–SiO_2 was synthesized via acid leaching followed by a staggered pyrolysis process, which preserved the unique spherical morphology of silica from the RH template, as depicted in Figure 2 (b). This contrasts with the irregular structure shown in Figure 2 (a), where alkaline dissolution and re-solidification altered the natural template. This resulted in a high surface area (228 $m^2.g^{-1}$) support that facilitated uniform Ni dispersion and minimized particle agglomeration, enabling over 95% conversion and selectivity for the target products. As Ni loading increased, a reduction in surface area was observed due to pore blockage, yet catalytic activity remained high, especially at the optimized 15 wt.% Ni content. These structural and surface properties, namely high porosity, and nanoscale metal dispersion are highly desirable for hydrogen storage systems. In particular, uniform metal dispersion and reduced particle size can lower activation barriers for

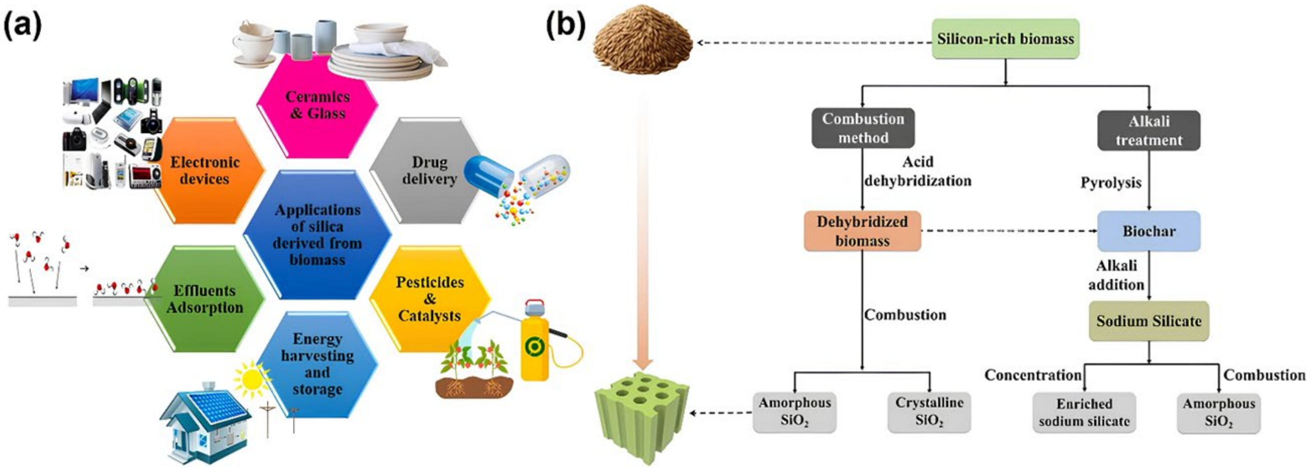

Figure 1. (a) Applications of biomass-derived functional materials and (b) Flow chart of silicon extraction from biomass. Adapted from Ramalingam *et al.* [32] and Kong *et al.* [31] with Elsevier permission.

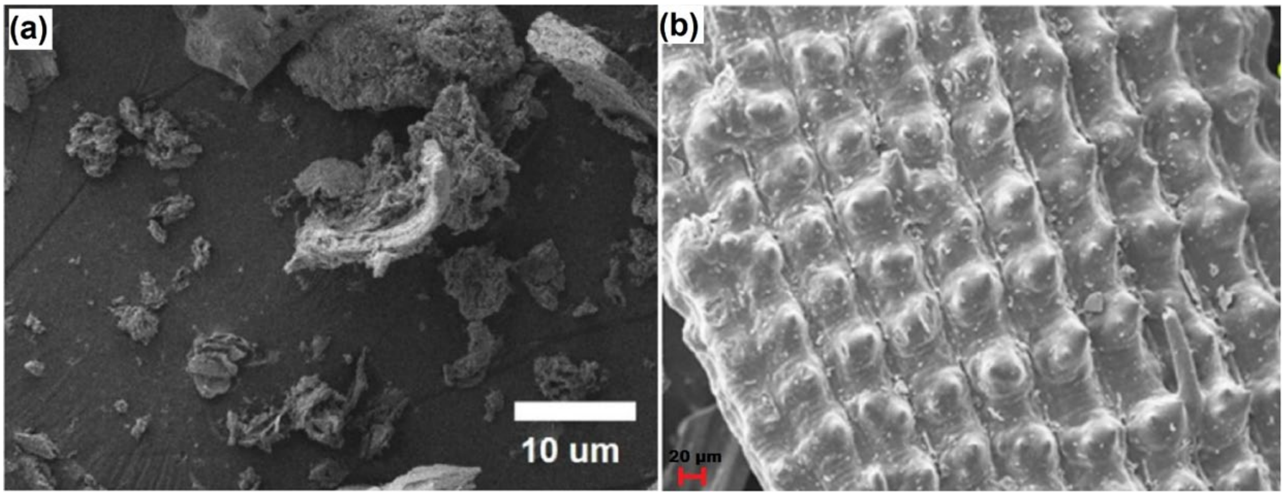

Figure 2. (a) SEM image of highly purified SiO_2 obtained from RH and (b) SEM image of C-SiO_2 derived from RH after acid leaching and staggered-pyrolysis. Adapted from Chun *et al.* [80] and Madduluri *et al.* [89] with Elsevier permission.

hydrogen sorption reactions, thereby improving kinetics. Meanwhile, the resistance to carbon fouling suggests long-term structural and catalytic stability, which is essential for maintaining thermodynamic reversibility over multiple cycles [8,69].

Beyond thermochemical processes, RH-derived Si-based materials have also been investigated as supports for Fenton catalysts, with iron (Fe) effectively deposited onto the silica surface [96–99]. Notably, two distinct synthetic approaches were employed, one retaining the intrinsic amorphous architecture of RH-SiO_2, and the other involving morphological reshaping via alkaline dissolution and acid reprecipitation according to Equations 3 and 4.

$$SiO_2 + 2NaOH \rightarrow Na_2SiO_3 + H_2O \tag{3}$$

$$Na_2SiO_3 + 2H^+ \rightarrow SiO_2 + H_2O + 2Na^+ \tag{4}$$

The former preserves the original hierarchical structure of RH, while the latter results in reconstructed, often less-ordered silica morphologies. This structural divergence is pivotal for hydrogen storage systems, as retaining the natural morphology can offer better-connected pore networks and higher structural integrity, which in turn support improved hydrogen diffusion and structural stability under repeated cycles. Moreover, the successful incorporation and dispersion of Fe as an active phase on these supports without severe particle aggregation or loss of surface accessibility demonstrates their suitability as platforms for hosting catalytic or hydride-active species. The controlled deposition of Fe also suggests potential for catalytic activation of hydrogenation or dehydrogenation reactions, potentially reducing energy barriers and enhancing overall sorption kinetics. Thus, even though these materials were developed for pollutant degradation, their surface chemistry, metal-loading tolerance, and morphology control present clear parallels to the design principles for advanced hydrogen storage materials.

While the silica dissolution and reprecipitation route is often considered a means to produce high-purity SiO_2 with enhanced sorptive surface [78,99]. This advantage is not guaranteed unless precipitation and post-treatment conditions are carefully controlled. As highlighted by Adam *et al.* [100], reprecipitated SiO_2 derived from RHA in the presence of Ruthenium ions (Ru-ions) exhibited a specific surface area of just 65 $m^2.g^{-1}$, which further plummeted to 10 $m^2.g^{-1}$ after calcination at 973 K. This dramatic loss of surface area likely resulted from the collapse of the porous network into globular, low-accessibility structures. Such an outcome underscores a critical caveat: a higher surface area is not an inherent trait of reprecipitated silica and, without meticulous control of precipitation and thermal treatment, the structural advantages of RH-derived silica may be compromised. In hydrogen storage applications, especially where nanoconfinement or catalyst dispersion is vital, this morphological collapse can severely impair hydrogen diffusion pathways and reduce the number of active interface sites, leading to sluggish sorption kinetics and limited thermodynamic reversibility [101]. Thus, achieving a balance between purity, morphology, and thermal robustness is essential. Controlled precipitation strategies that preserve mesoporosity and structural integrity not only optimize hydrogen accessibility but also stabilize the host matrix during thermal cycling, an imperative factor for long-term storage performance.

Bamboo, like RH, contains biogenic SiO_2 in its stems and leaves, though its SiO_2 content is subject to significant variability. Factors such as seasonality, geographical location, soil composition, and the specific bamboo part play a role in influencing silica concentration. In contrast to RH, bamboo and its derivatives have received less attention in research, largely due to the relatively lower Si-content in bamboo, with its leaves being the most promising source for silica extraction. Silica content in bamboo leaves has been reported to vary widely, ranging from 3.4% to 41 wt.%, largely influenced by the Si availability in the soil where the bamboo is grown [102]. This variability in Si content presents a challenge for standardizing bamboo-derived silica for catalytic applications.

A significant study by Fatimah *et al.* [103] focused on utilizing bamboo leaf ash (BLA) as a Si-rich catalyst. The as-synthesized BLA was found to contain 58.3 wt.% amorphous SiO_2, along with various impurities such as K, C, calcium (Ca), sulfur (S), Fe, and phosphorus (P). The absence of pretreatment steps, such as acid leaching or alkaline extraction, prior to calcination contributed to this composition. When used in a conventional reflux catalytic reaction, the BLA exhibited a moderate transesterification yield of approximately 40%. However, under microwave-assisted conditions, this yield was slightly enhanced to ~50%, demonstrating the impact of microwave energy, which induces vibrational and rotational activation in the substrate molecules. This remarkable enhancement can be attributed to the synergistic effects of increased surface area (56.12 $m^2.g^{-1}$ for BLA compared to 27.45 $m^2.g^{-1}$ for unmodified BLA) and the facilitated chemisorption of substrates on the acidic Zr-sites.

Summarizing the aforementioned studies, biomass-derived silica materials hold strong potential for hydrogen storage applications due to their natural porosity, surface reactivity, and adjustable composition. Their hydrogen sorption performance can be significantly improved through pre-treatment methods such as acid or alkaline leaching, thermal activation, or ion exchange, which remove impurities, increase surface area, and create active sites for faster hydrogen diffusion and better reaction pathways. Although rice husk is a widely used source, other biomass types, such as bamboo leaves, sugarcane bagasse, corn stalks, and oil palm residues, also offer sustainable and underutilized alternatives. With appropriate processing, these biogenic silica materials can serve as effective scaffolds or reactive matrices for metal hydrides, enabling nanoconfinement strategies that reduce particle agglomeration, lower activation energy, and enhance cycling stability in hydrogen storage systems.

Critical to these improvements are the intrinsic material attributes, high surface area, tailored porosity, and controlled morphology, which facilitate effective confinement of metal hydrides like MgH_2 by improving particle dispersion and shortening hydrogen diffusion pathways. The porous silica framework physically restricts MgH_2 particle growth during hydrogen cycling, maintaining nanoscale domains that offer more active surface area and better hydrogen accessibility. This confinement reduces the kinetic barriers for hydrogen absorption and desorption by enhancing gas transport through interconnected pores and increasing the interface between MgH_2 and the support [69]. Additionally, surface silanol groups and possible catalytic dopants on silica can promote reaction kinetics and improve thermodynamic reversibility. Together, these features directly contribute to enhanced hydrogen sorption kinetics and overall storage performance [7]. A summary of the different biomass sources, extraction methods, resulting silica features, and their potential application in hydrogen storage systems is presented in Table 1.

4.2. Key Factors Affecting the Characteristics of Silica Materials Derived from Biomass

The physicochemical properties of biomass-derived functional silica are strongly dependent on several key factors, notably the type of biomass feedstock, combustion parameters, and post-synthesis treatment methods. Variations in these parameters can significantly influence the silica yield, chemical purity, structural crystallinity, surface area, and porosity properties that are critical for optimizing performance in hydrogen storage applications. Importantly, these synthesis-dependent characteristics also govern the density, chemical nature, and accessibility of surface-active sites, such as silanol groups and defect sites, which directly control molecular hydrogen adsorption mechanisms.

Table 1. Summary of biomass-derived Silica preparation methods and their potential application in hydrogen storage.

Biomass Source	Extraction Method	Processing Conditions	Resulting Silica Features	Implications for Hydrogen Storage
Rice Husk	Acid leaching + combustion	HCl/H_2SO_4 pre-treatment; calcination at 500-800 °C	High-purity amorphous SiO_2; high surface area (297–895 m^2/g); mesopores (3-60 nm)	Enables nanoconfinement; enhances hydrogen adsorption kinetics and structural stability
Rice Husk	Alkaline extraction (NaOH)	Pyrolysis (400-700 °C) → NaOH treatment → precipitation	Sodium silicate precursor; tunable porosity and morphology (via surfactants)	Allows design of tailored pore architectures; improves hydrogen diffusion and accessibility
Rice Husk	Acid leaching + staged pyrolysis	HCl treatment followed by controlled pyrolysis	Carbon-silica (C-SiO_2) composite with spherical morphology; surface area ~228 m^2/g	Promotes uniform metal dispersion; reduces nanoparticle agglomeration; supports catalytic enhancement
Sugarcane Bagasse	Acid and alkaline treatment	Calcination → HCl leaching → NaOH extraction	Silica purity up to 88.13%; sodium silicate intermediate.	Similar to RH processes; supports mesostructured silica for catalyst support
Ground Straw	Carbonization + alkaline treatment	Carbonization at 800 °C → NaOH treatment → silicate extraction	Sodium silicate; mesoporous silica precursor	Offers adaptable structure; suitable for optimizing hydrogen sorption characteristics
Bamboo Leaves	Direct calcination (no pretreatment)	Ash production via direct calcination	~58.3 wt.% amorphous SiO_2; surface area ~56.12 m^2/g	Low-cost and simple approach; limited purity and performance without additional treatment
Rice Husk (Reprecipitated)	Alkaline dissolution + acid precipitation	NaOH dissolution + HCl precipitation; calcination at 973 K	Risk of pore collapse; surface area reduction from 65 to 10 m^2/g	Demonstrates importance of process control; poor porosity compromises hydrogen storage
Rice Husk-SiO_2 with Fe	Surface deposition + morphology control	Fe loading on amorphous or reprecipitated SiO_2	Retained or modified RH-derived silica morphology; controlled Fe dispersion	Enhances catalytic activity and hydrogen sorption; maintains structural integrity during cycling

Feedstock Selection: Biomass-derived silica feedstocks vary widely in silicon content, morphology, and reactivity, all of which directly influence their suitability for hydrogen storage applications. Plants from the Gramineae and Cyperaceae families are known to accumulate high levels of biogenic silica [104], making them promising candidates for silica-based hydrogen sorbents or scaffold materials. Among these, RHA, with a silicon content approaching 90%, offers a particularly rich source. Other notable feedstocks, such as bamboo leaf ash (60–80%), wheat straw (>80%), corncob (>60%), and sugarcane bagasse, also contain significant amounts of SiO_2, underlining their potential for scalable and sustainable silica production [31]. Moreover, the intrinsic microstructure of biosilica varies by source and can significantly impact hydrogen uptake performance. Rice husk-derived silica, for instance, features a naturally templated mesoporous architecture with a high surface area, which facilitates faster hydrogen diffusion and increased active site accessibility [105]. These properties are essential in supporting metal hydrides or catalytic nanoparticles, especially in nanoconfined hydrogen storage systems, where kinetics are heavily dependent on interfacial contact and diffusion pathways. A comparative summary of these biomass sources, including their SiO_2 content, structural characteristics, and implications for hydrogen storage, is provided in Table 2. These feedstock-dependent structural features ultimately determine the abundance of surface silanol groups and defect-related active sites that act as molecular adsorption centers for hydrogen.

Diatoms present a unique biosilica source with highly ordered nanoscale porosity and a hierarchical framework [106,107], offering further advantages for hydrogen storage. Their siliceous frustules have been used to synthesize zeolitic structures (LTA zeolite-type), which display well-defined micropores and sharp crystal morphology as shown in Figure 3 [108]. These features enhance hydrogen adsorption through improved surface accessibility, pore confinement effects, and optimized thermodynamic interactions, critical parameters for both physisorption and chemisorption systems. These feedstock-dependent structural features ultimately determine the distribution of silanol groups and defect-related active sites responsible for molecular hydrogen adsorption.

Conditions of Combustion: The combustion parameters used in biomass processing play a decisive role in tailoring the physicochemical characteristics of silica relevant for hydrogen storage systems. Temperature, atmosphere, and combustion duration directly affect the surface area, porosity, crystallinity, and purity of the resulting SiO_2, key factors governing its effectiveness as a scaffold or support for hydrogen sorbents [109]. Temperature, in particular, has a profound influence on both silica purity and textural properties. While an increase in combustion temperature is generally associated with improved silica purity due to the enhanced removal of organic and carbonaceous matter [110], excessive temperatures can adversely affect the surface characteristics crucial for hydrogen uptake. For example, during the combustion of rice husk, temperatures above 500 °C can lead to the volatilization and re-condensation of organics that obstruct pore channels, thereby limiting oxygen diffusion and resulting in incomplete carbon removal [111]. Such residue contamination diminishes silica purity and impairs its interfacial compatibility with hydrogen-active species, such as MgH_2 or transition metals.

Table 2. Comparative SiO_2 content and structural features of biomass-derived silica for hydrogen storage applications.

Biomass Source	SiO_2 Content (wt.%)	Key Structural Characteristics	Implications for Hydrogen Storage
Rice Husk Ash	~90%	Naturally templated mesoporous structure; high surface area	Enhances hydrogen diffusion and accessibility to active sites
Bamboo Leaf Ash	60-80%	Variable structure; influenced by seasonality and soil conditions	Moderate surface area; promising for catalytic applications with suitable treatment
Wheat Straw	>80%	Depends on combustion/processing conditions	Potential for mesoporous structure; suitable precursor with appropriate processing
Corncob	>60%	Microporous features after treatment	Viable for supporting catalysts or hydrides
Sugarcane Bagasse	~6-70% (varies)	Amorphous silica after acid-alkali treatment	Can produce mesoporous silica; useful for metal dispersion and hydrogen activation

Moreover, temperature-induced structural evolution significantly impacts silica's surface area and porosity attributes vital for fast hydrogen kinetics and high storage capacities. Zeng *et al.* [82] observed that increasing the combustion temperature from 400 °C to 550 °C marginally enhanced the specific surface area of rice husk-derived silica from 484 to 518 $m^2.g^{-1}$. However, a further increase to 700 °C led to a drastic drop to 211 $m^2.g^{-1}$, attributed to particle sintering and pore collapse. Such a loss in specific surface area and pore volume directly reduces hydrogen adsorption sites and limits the efficiency of nanoconfined hydrogen systems. In terms of crystalline phase, high-temperature combustion can also lead to the formation of crystalline phases such as mullite, which is thermodynamically stable but chemically inert [112]. While amorphous silica offers high surface reactivity and dispersion capabilities for metal hydrides or catalysts, mullite formation reduces surface activity and hinders further functionalization, detrimental to applications involving hydrogen storage where interaction at the silica-metal interface is critical. Such temperature-induced phase and surface transformations directly regulate the availability of hydrogen-active surface sites, including hydroxyl groups and defect centers, thereby influencing molecular adsorption strength and hydrogen sorption kinetics.

Treatment Conditions: Chemical pretreatment primarily involving acid and alkali treatments, is a crucial step in tailoring silica derived from biomass for applications in hydrogen storage, especially as nanoconfinement scaffolds. The selection of chemical reagents, extraction time, and temperature significantly influence the morphology, crystallinity, purity, surface chemistry, and ultimately the effectiveness of silica in hosting hydrogen-active species such as metal hydrides. Acid and alkali treatments operate via distinct mechanisms. Acid treatment is predominantly used for demineralization, selectively removing metal oxides while preserving or enhancing the siloxane (Si-O-Si) network. This process yields silica with higher purity and often improved crystallinity. Anuar *et al.* [113] demonstrated that silica obtained from acid treatment retains a more ordered siloxane structure, which can facilitate stronger interfacial bonding with confined hydrogen storage materials. Ghorbani *et al.* [114] further showed that acid leaching followed by thermal treatment increased SiO_2 content from 33.14% to 87.25%, a critical enhancement for minimizing inert phases that can hinder hydrogen sorption kinetics. Conversely, alkali treatment, typically involving strong bases like NaOH or KOH, dissolves silica precursors through the breakdown of the siloxane network [87]. While this produces amorphous silica with potentially higher porosity, the structural disorder can reduce the mechanical stability of the scaffold, which is detrimental during repetitive hydrogen absorption and desorption cycling. Thus, a combined strategy, initial acid leaching followed by controlled alkali extraction is often employed to balance purity, structure, and porosity.

Time and temperature of treatment also play pivotal roles. Liou *et al.* [115] observed that the specific surface area of rice husk-derived silica initially increased with aging time, peaking at 380 $m^2.g^{-1}$ before declining due to particle growth and aggregation. This non-linear trend highlights the importance of optimizing reaction kinetics to prevent excessive gelation or pore collapse, which reduces available sites for hydrogen adsorption. For hydrogen storage applications, maximizing silica's surface area, mesoporosity, and purity is paramount. These attributes enable uniform metal dispersion, reduce activation energy barriers for hydrogen desorption, and improve structural durability. Therefore, pretreatment conditions must be carefully tuned not only to enhance extraction efficiency but also to optimize the density and accessibility of surface-active sites responsible for molecular hydrogen adsorption and spillover processes.

5. Conclusion, Challenges and Future Prospects

Biomass-derived silica presents a sustainable and versatile platform for advancing hydrogen storage technologies. Extracted from abundant renewable sources such as rice husk, bamboo leaves, sugarcane bagasse, and other agricultural residues, silica is typically obtained through acid leaching to remove metallic impurities, followed by thermal combustion or alkaline extraction processes. These synthesis routes not only yield high-purity amorphous SiO_2 but also enable precise control over critical material properties, including surface area, pore volume, and morphology. Such attributes are essential for effectively confining metal hydrides like MgH_2, as they reduce particle agglomeration, lower hydrogen diffusion barriers, and improve overall sorption kinetics.

Moreover, the surface chemistry of biomass-derived silica allows for functionalization with catalytic elements such as Fe or Ni, offering a dual function of physical confinement and catalytic enhancement. These capabilities contribute to improved hydrogen desorption/absorption kinetics, reduced activation energy, and enhanced cycling stability. Continued optimization of synthesis parameters, such as calcination temperature, leaching concentration, and surfactant-assisted structuring, holds promise for further improving hydrogen storage capacity and long-term material performance.

Despite these advantages, several challenges must be addressed. Current synthesis procedures often involve energy-intensive steps and the use of strong acids or bases, raising environmental and economic concerns. Developing greener and more scalable extraction and functionalization approaches is imperative. Although no studies to date have directly investigated the use of mesoporous or hollow-structured biomass-derived silica in hydrogen storage systems, these morphologies, well-known for enhancing hydrogen diffusion in other porous materials, represent a promising avenue for future exploration. Further research is needed to optimize such architectures and assess their structural integrity under cycling conditions. Future efforts should also integrate techno-economic analysis and life-cycle assessments to evaluate the commercial viability and environmental footprint of these materials. The application of machine learning and data-driven material design may further accelerate the discovery of optimal structure–property–performance relationships. By addressing these scientific and engineering challenges, biomass-derived silica materials could play a pivotal role in next-generation hydrogen storage systems, offering a pathway toward clean, efficient, and circular energy solutions.

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Declaration of Generative AI Use

Generative AI-assisted tools were used only to enhance the language and readability of the manuscript. All content was reviewed and approved by the authors, who are fully responsible for the work.

Conflict of interest

The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this article.

CRedit Author Statement

Author Contributions: M. F. Saeid: Conceptualization, methodology, literature collection, formal analysis, and original draft preparation. B. A. Abdulkadir: Critical review, editing, conceptual input, data visualization, and validation of content. H. D. Setiabudi: Supervision, project administration, resources, manuscript review and editing, validation, and overall guidance. All authors have read and agreed to the published version of the manuscript.

References

[1] Saeid, M.F., Abdulkadir, B.A., Ismail, M., Setiabudi, H.D. (2025). A Bibliometric Analysis of Metal-Based Catalysts for Efficient Hydrogen Production. *Environmental Quality Management*, 34(3), e70046. DOI: 10.1002/tqem.70046.

[2] Saeid, M.F., Abdulkadir, B.A., Abidin, S.Z., Setiabudi, H.D. (2025). Nanoconfinement of magnesium hydride in porous scaffolds for hydrogen storage: Kinetics, thermodynamics, and future prospects. *Materials Science in Semiconductor Processing*, 188, 109225. DOI: 10.1016/j.mssp.2024.109225.

[3] Becherif, M., Ramadan, H.S., Cabaret, K., Picard, F., Simoncini, N., Bethoux, O. (2015). Hydrogen Energy Storage: New Techno-Economic Emergence Solution Analysis. In: *Energy Procedia.* DOI: 10.1016/j.egypro.2015.07.629.

[4] Kumar, A., Kumar, K., Kaushik, N., Sharma, S., Mishra, S. (2010). Renewable energy in India: Current status and future potentials. *Renewable and Sustainable Energy Reviews,* 14(8), 2434-2442. DOI: 10.1016/j.rser.2010.04.003.

[5] Saeid, M.F., Abdulkadir, B.A., Fauzi, M.A., Setiabudi, H.D. (2025). Carbon Materials for Hydrogen Storage: A Bibliometric Analysis on Current Trends and Future Prospects. *Environmental Quality Management*, 34(4), e70109. DOI: 10.1002/tqem.70109.

[6] Zohri, M., Suwarno, S., Haryadi, H., Fudholi, A. (2025). Review of hydrogen storage sustainability using bibliometric and mathematical modeling analysis. *Journal of Energy Storage*, 123, 116710. DOI: 10.1016/j.est.2025.116710.

[7] Saeid, M.F., Abdulkadir, B.A., Setiabudi, H.D. (2025). Enhancing hydrogen adsorption performance of hollow silica spheres through the addition of Fe: A study on kinetic and thermodynamic. *Materials Science in Semiconductor Processing*, 192, 109458. DOI: 10.1016/j.mssp.2025.109458.

[8] Saeid, M.F., Abdulkadir, B.A., Setiabudi, H.D. (2025). Tailoring Hollow Silica Spheres for Enhanced Hydrogen Adsorption Performance: Role of Synthesis Parameters. *Energy Technology*, 13(6), 2500078. DOI: 10.1002/ente.202500078.

[9] Abubakar Abdulkadir, B., Jalil, A.A., Cheng, C.K., Setiabudi, H. (2023). Progress and Advances in Porous Silica-based Scaffolds for Enhanced Solid-state Hydrogen Storage: A Systematic Literature Review. *Chem. Asian J.* 19(2), e202300833. DOI: 10.1002/asia.202300833

[10] Rowsell, J.L.C., Yaghi, O.M. (2005). Strategies for hydrogen storage in metal-organic frameworks. *Angewandte Chemie - International Edition,* 44(30), 4670-4679. DOI: 10.1002/anie.200462786.

[11] Schlapbach, L., Züttel, A. (2001). Hydrogen-storage materials for mobile applications. *Nature*, 414(6861), 353–358. DOI: 10.1038/35104634.

[12] Abdulkadir, B.A., Teh, L.P., Rahman Khan, M.M., Setiabudi, H.D. (2024). Potential Applications of Metal-Doped Nanomaterials for Enhancing Solid-State Hydrogen Storage. *ChemistrySelect*, 9(14), e202400051. DOI: 10.1002/slct.202400051.

[13] Sazelee, N.A., Ismail, M. (2021). Recent advances in catalyst-enhanced $LiAlH_4$ for solid-state hydrogen storage: A review. *Int. J. Hydrogen Energy,* 46(13), 9123-9141. DOI: 10.1016/j.ijhydene.2020.12.208.

[14] Ouyang, L.Z., Dong, H.W., Peng, C.H., Sun, L.X., Zhu, M. (2007). A new type of Mg-based metal hydride with promising hydrogen storage properties. *International Journal of Hydrogen Energy*, 32(16) DOI: 10.1016/j.ijhydene.2007.05.026.

[15] Andersson, J., Grönkvist, S. (2019). Large-scale storage of hydrogen. *Int. J. Hydrogen Energy,* 44, 11901–11919. DOI: 10.1016/j.ijhydene.2019.03.063.

[16] Schlapbach, L., Züttel, A. (2001). Hydrogen-storage materials for mobile applications. *Nature*, 414(6861), 353–358. DOI: 10.1038/35104634.

[17] Ren, J., Musyoka, N.M., Langmi, H.W., Mathe, M., Liao, S. (2017). Current research trends and perspectives on materials-based hydrogen storage solutions: A critical review. *Int. J. Hydrogen Energy,* 42(1), 289-311. DOI: 10.1016/j.ijhydene.2016.11.195.

[18] Kim, H., So, S.H., Muhammad, R., Oh, H. (2024). Comparing the practical hydrogen storage capacity of porous adsorbents: Activated carbon and metal-organic framework. *International Journal of Hydrogen Energy*, 50 DOI: 10.1016/j.ijhydene.2023.10.160.

[19] Mohan, M., Sharma, V.K., Kumar, E.A., Gayathri, V. (2019). Hydrogen storage in carbon materials-A review. *Energy Storage*, 1(2), e35. DOI: 10.1002/est2.35.

[20] Wen, Y., Chai, X., Gu, Y., Wu, W., Ma, W., Zhang, J., Zhang, T. (2025). Advances in hydrogen storage materials for physical H_2 adsorption. *International Journal of Hydrogen Energy*, 97, 1261–1274. DOI: 10.1016/j.ijhydene.2024.11.459.

[21] Abdulkadir, B.A., Ismail, M., Setiabudi, H.D. (2024). Enhancing hydrogen adsorption through optimized magnesium dispersion on fibrous nano-silica scaffold: Kinetic and thermodynamic studies. *Microporous and Mesoporous Materials*, 378, 113232. DOI: 10.1016/j.micromeso.2024.113232.

[22] Bera, B., Das, N. (2019). Synthesis of high surface area mesoporous silica SBA-15 for hydrogen storage application. *International Journal of Applied Ceramic Technology*, 16(1), 294–303. DOI: 10.1111/ijac.13082.

[23] Ciocarlan, R.-G., Farrando-Perez, J., Arenas-Esteban, D., Houlleberghs, M., Daemen, L.L., Cheng, Y., Ramirez-Cuesta, A.J., Breynaert, E., Martens, J., Bals, S., Silvestre-Albero, J., Cool, P. (2024). Tuneable mesoporous silica material for hydrogen storage application via nano-confined clathrate hydrate construction. *Nature Communications*, 15(1), 8697. DOI: 10.1038/s41467-024-52893-3.

[24] Hasan, R., Chong, C.C., Bukhari, S.N., Jusoh, R., Setiabudi, H.D. (2019). Effective removal of Pb(II) by low-cost fibrous silica KCC-1 synthesized from silica-rich rice husk ash. *Journal of Industrial and Engineering Chemistry*, 75, 262–270. DOI: 10.1016/j.jiec.2019.03.034.

[25] Norsuraya, S., Fazlena, H., Norhasyimi, R. (2016). Sugarcane Bagasse as a Renewable Source of Silica to Synthesize Santa Barbara Amorphous-15 (SBA-15). In: *Procedia Engineering*. DOI: 10.1016/j.proeng.2016.06.627.

[26] Tan, M., Li, X., Feng, Y., Wang, B., Han, L., Bao, W., Chang, L., Wang, J. (2023). Fly ash-derived mesoporous silica with large pore volume for augmented CO2 capture. *Fuel*, 351. DOI: 10.1016/j.fuel.2023.128874.

[27] Dileep, P., Varghese, G.A., Sivakumar, S., Narayanankutty, S.K. (2020). An innovative approach to utilize waste silica fume from zirconia industry to prepare high performance natural rubber composites for multi-functional applications. *Polymer Testing*, 81. DOI: 10.1016/j.polymertesting.2019.106172.

[28] Jiang, X., Tang, X., Tang, L., Zhang, B., Mao, H. (2019). Synthesis and formation mechanism of amorphous silica particles via sol–gel process with tetraethylorthosilicate. *Ceramics International*, 45(6). DOI: 10.1016/j.ceramint.2019.01.067.

[29] Zulfiqar, U., Subhani, T., Wilayat Husain, S. (2016). Synthesis of silica nanoparticles from sodium silicate under alkaline conditions. *Journal of Sol-Gel Science and Technology*, 77(3). DOI: 10.1007/s10971-015-3950-7.

[30] Elyasi, S., Saha, S., Hameed, N., Mahon, P.J., Juodkazis, S., Salim, N. (2024). Emerging trends in biomass-derived porous carbon materials for hydrogen storage. *Int. J. Hydrogen Energy,* 62 (10), 272-306. DOI: 10.1016/j.ijhydene.2024.02.337.

[31] Kong, Z., Zhang, H., Zhou, T., Xie, L., Wang, B., Jiang, X. (2025). Biomass-derived functional materials: Preparation, functionalization, and applications in adsorption and catalytic separation of carbon dioxide and other atmospheric pollutants. *Separation and Purification Technology*, 354, 129099. DOI: 10.1016/j.seppur.2024.129099.

[32] Ramalingam, G., Priya, A.K., Gnanasekaran, L., Rajendran, S., Hoang, T.K.A. (2024). Biomass and waste derived silica, activated carbon and ammonia-based materials for energy-related applications – A review. *Fuel*, 355, 129490. DOI: 10.1016/j.fuel.2023.129490.

[33] Chen, K., Ng, K.H., Cheng, C.K., Cheng, Y.W., Chong, C.C., Vo, D.V.N., Witoon, T., Ismail, M.H. (2022). Biomass-derived carbon-based and silica-based materials for catalytic and adsorptive applications- An update since 2010. *Chemosphere*, 287, 132222. DOI: 10.1016/j.chemosphere.2021.132222.

[34] Ouyang, L., Chen, K., Jiang, J., Yang, X.S., Zhu, M. (2020). Hydrogen storage in light-metal based systems: A review. *Journal of Alloys and Compounds*, 829, 154597. DOI: 10.1016/j.jallcom.2020.154597.

[35] Saxena, R.C., Adhikari, D.K., Goyal, H.B. (2009). Biomass-based energy fuel through biochemical routes: A review. *Renewable and Sustainable Energy Reviews,* 13(1), 167-178. DOI: 10.1016/j.rser.2007.07.011.

[36] Larichev, Y. V., Yeletsky, P.M., Yakovlev, V.A. (2015). Study of silica templates in the rice husk and the carbon-silica nanocomposites produced from rice husk. *Journal of Physics and Chemistry of Solids*, 87, 58-63. DOI: 10.1016/j.jpcs.2015.07.025.

[37] Pieła, A., Żymańczyk-Duda, E., Brzezińska-Rodak, M., Duda, M., Grzesiak, J., Saeid, A., Mironiuk, M., Klimek-Ochab, M. (2020). Biogenic synthesis of silica nanoparticles from corn cobs husks. Dependence of the productivity on the method of raw material processing. *Bioorganic Chemistry*, 99, 103773. DOI: 10.1016/j.bioorg.2020.103773.

[38] Irzaman, Oktaviani, N., Irmansyah (2018). Ampel Bamboo Leaves Silicon Dioxide (SiO_2) Extraction. In: *IOP Conference Series: Earth and Environmental Science.* DOI: 10.1088/1755-1315/141/1/012014.

[39] Bortolotto Teixeira, L., Guzi de Moraes, E., Paolinelli Shinhe, G., Falk, G., Novaes de Oliveira, A.P. (2021). Obtaining Biogenic Silica from Sugarcane Bagasse and Leaf Ash. *Waste and Biomass Valorization*, 12(6), 3205-3221. DOI: 10.1007/s12649-020-01230-y.

[40] Norul Azlin, M.Z., Syamim Syufiana, S. (2022). The preparation and characterization of silica from coconut husk. In: *Journal of Physics: Conference Series.* DOI: 10.1088/1742-6596/2266/1/012011.

[41] Bhagiyalakshmi, M., Yun, L.J., Anuradha, R., Jang, H.T. (2010). Utilization of rice husk ash as silica source for the synthesis of mesoporous silicas and their application to CO_2 adsorption through TREN/TEPA grafting. *Journal of Hazardous Materials*, 175(1–3). DOI: 10.1016/j.jhazmat.2009.10.097.

[42] Vaibhav, V., Vijayalakshmi, U., Roopan, S.M. (2015). Agricultural waste as a source for the production of silica nanoparticles. *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy*, 139, 515-520. DOI: 10.1016/j.saa.2014.12.083.

[43] Dixit, S., Van Cappellen, P. (2002). Surface chemistry and reactivity of biogenic silica. *Geochimica et Cosmochimica Acta*, 66(14), 2559-2568. DOI: 10.1016/S0016-7037(02)00854-2.

[44] Rimola, A., Costa, D., Sodupe, M., Lambert, J.F., Ugliengo, P. (2013). Silica surface features and their role in the adsorption of biomolecules: Computational modeling and experiments. *Chem. Rev.* 113(6), 4216-4. DOI: 10.1021/cr3003054.

[45] Morales-Paredes, C.A., Rodríguez-Linzán, I., Saquete, M.D., Luque, R., Osman, S.M., Boluda-Botella, N., Joan Manuel, R.D. (2023). Silica-derived materials from agro-industrial waste biomass: Characterization and comparative studies. *Environmental Research*, 231, 116002. DOI: 10.1016/j.envres.2023.116002.

[46] Huang, R.A., Hu, X., Guo, Y., Wang, J., Yang, B. (2020). Highly Hierarchical Fibrillar Biogenic Silica with Mesoporous Structure Derived from the Perennial Plant Equisetum Fluviatile. *ACS Applied Materials and Interfaces*, 12(31), 35259-35265. DOI: 10.1021/acsami.0c10421.

[47] Liu, X., Xia, Z., Diao, R., Qi, F., Zhang, Y., Ma, P. (2024). Rice husk-based biogenic silica-anchored Sn-Co bimetallic catalysts for cellulose hydrogenolysis: Structural regulation and mechanism study. *Molecular Catalysis*, 555, 113861. DOI: 10.1016/j.mcat.2024.113861.

[48] Franco, A., Luque, R., Carrillo-Carrión, C. (2021). Exploiting the potential of biosilica from rice husk as porous support for catalytically active iron oxide nanoparticles. *Nanomaterials*, 11(5), 1259. DOI: 10.3390/nano11051259.

[49] Abdulkadir, B.A., Setiabudi, H.D. (2025). Bibliometric insights into metal-organic frameworks modified with metal-based materials for hydrogen storage: Prospects, opportunities and challenges. *Journal of the Taiwan Institute of Chemical Engineers*, 167, 105893. DOI: 10.1016/j.jtice.2024.105893.

[50] Abdulkadir, B.A., Mohd Zaki, R.S.R., Abd Wahab, A.T., Miskan, S.N., Nguyen, A.-T., Vo, D.-V.N., Setiabudi, H.D. (2024). A concise review on surface and structural modification of porous zeolite scaffold for enhanced hydrogen storage. *Chinese Journal of Chemical Engineering*, 70, 33–53. DOI: 10.1016/j.cjche.2024.03.001.

[51] Gao, T.F., Zhang, H. (2014). Multiscale study on hydrogen storage based on covalent organic frameworks. *Structural Chemistry*, 25(2), 503-513. DOI: 10.1007/s11224-013-0319-9.

[52] Rather, S. ullah (2020). Preparation, characterization and hydrogen storage studies of carbon nanotubes and their composites: A review. *Int. J. Hydrogen Energy,* 45(7), 4653-4572. DOI: 10.1016/j.ijhydene.2019.12.055.

[53] Ayinla, R.T., Dennis, J.O., Zaid, H.M., Sanusi, Y.K., Usman, F., Adebayo, L.L. (2019). A review of technical advances of recent palm bio-waste conversion to activated carbon for energy storage. *J. Clean. Prod.* 229 (20), 1427-1442. DOI: 10.1016/j.jclepro.2019.04.116.

[54] Ruiz-Cornejo, J.C., Sebastián, D., Lázaro, M.J. (2020). Synthesis and applications of carbon nanofibers: A review. *Reviews in Chemical Engineering,* 36(4), 1-19. DOI: 10.1515/revce-2018-0021.

[55] Spyrou, K., Gournis, D., Rudolf, P. (2013). Hydrogen Storage in Graphene-Based Materials: Efforts Towards Enhanced Hydrogen Absorption. *ECS Journal of Solid State Science and Technology*, 2(10), M3160. DOI: 10.1149/2.018310jss.

[56] Niaz, S., Manzoor, T., Pandith, A.H. (2015). Hydrogen storage: Materials, methods and perspectives. *Renewable and Sustainable Energy Reviews,* 50, 457-469. DOI: 10.1016/j.rser.2015.05.011.

[57] Akhayere, E., Kavaz, D., Vaseashta, A. (2022). Efficacy Studies of Silica Nanoparticles Synthesized Using Agricultural Waste for Mitigating Waterborne Contaminants. *Applied Sciences (Switzerland),* 12(18), 9279. DOI: 10.3390/app12189279.

[58] Mujtaba, M., Fernandes Fraceto, L., Fazeli, M., Mukherjee, S., Savassa, S.M., Araujo de Medeiros, G., do Espírito Santo Pereira, A., Mancini, S.D., Lipponen, J., Vilaplana, F. (2023). Lignocellulosic biomass from agricultural waste to the circular economy: a review with focus on biofuels, biocomposites and bioplastics. *J. Clean. Prod.* 402, 136815. DOI: 10.1016/j.jclepro.2023.136815.

[59] Anupam, K., Sharma, A.K., Lal, P.S., Dutta, S., Maity, S. (2016). Preparation, characterization and optimization for upgrading Leucaena leucocephala bark to biochar fuel with high energy yielding. *Energy*, 106(1), 743-756. DOI: 10.1016/j.energy.2016.03.100.

[60] Hunt, J.D., Nascimento, A., Zakeri, B., Jurasz, J., Dąbek, P.B., Barbosa, P.S.F., Brandão, R., de Castro, N.J., Leal Filho, W., Riahi, K. (2022). Lift Energy Storage Technology: A solution for decentralized urban energy storage. *Energy*, 254, 124102. DOI: 10.1016/j.energy.2022.124102.

[61] Salmi, M. Al (2024). Hydrogen Spillover Mechanisms on Copper on Zinc Oxide-Based Catalysts for Carbon Dioxide Hydrogenation to Methanol. *Johnson Matthey Technology Review*, 68(2), 184-200. DOI: 10.1595/205651324x16980703569747.

[62] Zhuravlev, L.T. (2000). The surface chemistry of amorphous silica. Zhuravlev model. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 173(1–3), 1-38. DOI: 10.1016/S0927-7757(00)00556-2.

[63] Bhatia, S.K., Myers, A.L. (2006). Optimum conditions for adsorptive storage. *Langmuir*, 22(4), 1-13. DOI: 10.1021/la0523816.

[64] Psofogiannakis, G.M., Froudakis, G.E. (2011). Fundamental studies and perceptions on the spillover mechanism for hydrogen storage. *Chemical Communications*, 47(28), 7933-7943. DOI: 10.1039/c1cc11389e.

[65] Cheng, H., Chen, L., Cooper, A.C., Sha, X., Pez, G.P. (2008). Hydrogen spillover in the context of hydrogen storage using solid-state materials. *Energy and Environmental Science*, 1(3), 338-354. DOI: 10.1039/b807618a.

[66] Sun, G., Xue, P., Wang, L., Zhang, X., Sun, G., Wang, Z., Zhang, Q., Zhang, P., Liu, Y., Pan, Y. (2025). Tracking the hydrogen spillover of heterogeneous catalysts in hydrogenation: from formation, migration, and regulation to fate. *Green Chemistry,* 27, 11739-11768. DOI: 10.1039/D5GC02983J.

[67] Li, Y., Zhao, D., Wang, Y., Xue, R., Shen, Z., Li, X. (2007). The mechanism of hydrogen storage in carbon materials. *International Journal of Hydrogen Energy*, 32(13), 2513-2517. DOI: 10.1016/j.ijhydene.2006.11.010.

[68] Li, H., Chen, X., Shen, D., Wu, F., Pleixats, R., Pan, J. (2021). Functionalized silica nanoparticles: Classification, synthetic approaches and recent advances in adsorption applications. *Nanoscale,* 13, 15998-16016. DOI: 10.1039/D1NR04048K.

[69] Saeid, M.F., Abdulkadir, B.A., Ismail, M., Setiabudi, H.D. (2025). Hydrogen storage in MgH_2 catalyzed by Fe nanoparticles and hollow silica spheres. *Fuel,* 400, 135635. DOI: 10.1016/j.fuel.2025.135635.

[70] Malahayati, M., Yufita, E., Ismail, I., Mursal, M., Idroes, R., Jalil, Z. (2021). The Effect of Natural Silica from Rice Husk Ash and Nickel as a Catalyst on the Hydrogen Storage Properties of MgH_2. *Journal of Ecological Engineering*, 22, 79–85. DOI: 10.12911/22998993/142959.

[71] Hou, Q., Yang, X., Zhang, J. (2021). Review on Hydrogen Storage Performance of MgH_2: Development and Trends. *ChemistrySelect,* 6, 1589–1606. DOI: 10.1002/slct.202004476.

[72] Konarova, M., Tanksale, A., Norberto Beltramini, J., Qing Lu, G. (2013). Effects of nano-confinement on the hydrogen desorption properties of MgH_2. *Nano Energy*, 2(1), 98-104. DOI: 10.1016/j.nanoen.2012.07.024.

[73] Mussabek, G., Yar-Mukhamedova, G., Orazbayev, S., Skryshevsky, V., Lysenko, V. (2025). Silicon Nanostructures for Hydrogen Generation and Storage. *Nanomaterials,* 15(19), 1531. DOI: 10.3390/nano15191531

[74] Zhao, S., Wang, Z.H., Wang, J.Y., Wang, P.F., Liu, Z.L., Shu, J., Yi, T.F. (2025). Unveiling the mysteries of hydrogen spillover phenomenon in hydrogen evolution reaction: Fundamentals, evidence and enhancement strategies. *Coord. Chem. Rev.* 524(1), 216321. DOI: 10.1016/j.ccr.2024.216321.

[75] Yuan, M., Guo, X., Liu, Y., Pang, H. (2019). Si-based materials derived from biomass: Synthesis and applications in electrochemical energy storage. *Journal of Materials Chemistry A*, 7(39), 22123-22147. DOI: 10.1039/c9ta06934h.

[76] Tuck, C.O., Pérez, E., Horváth, I.T., Sheldon, R.A., Poliakoff, M. (2012). Valorization of biomass: Deriving more value from waste. *Science*, 337, 696-699. DOI: 10.1126/science.1218930

[77] Jung, D.S., Ryou, M.H., Sung, Y.J., Park, S. Bin, Choi, J.W. (2013). Recycling rice husks for high-capacity lithium battery anodes. *Proceedings of the National Academy of Sciences of the United States of America*, 110(30), 12229-12234. DOI: 10.1073/pnas.1305025110.

[78] Elimbinzi, E., Nyandoro, S.S., Mubofu, E.B., Manayil, J.C., Lee, A.F., Wilson, K. (2020). Valorization of rice husk silica waste: Organo-amine functionalized castor oil templated mesoporous silicas for biofuels synthesis. *Microporous and Mesoporous Materials*, 294, 109868. DOI: 10.1016/j.micromeso.2019.109868.

[79] Rattanachu, P., Toolkasikorn, P., Tangchirapat, W., Chindaprasirt, P., Jaturapitakkul, C. (2020). Performance of recycled aggregate concrete with rice husk ash as cement binder. *Cement and Concrete Composites*, 108, 103533. DOI: 10.1016/j.cemconcomp.2020.103533.

[80] Chun, J., Mo Gu, Y., Hwang, J., Oh, K.K., Lee, J.H. (2020). Synthesis of ordered mesoporous silica with various pore structures using high-purity silica extracted from rice husk. *Journal of Industrial and Engineering Chemistry*, 81, 135-143. DOI: 10.1016/j.jiec.2019.08.064.

[81] de Cordoba, M.C.F., Matos, J., Montaña, R., Poon, P.S., Lanfredi, S., Praxedes, F.R., Hernández-Garrido, J.C., Calvino, J.J., Rodríguez-Aguado, E., Rodríguez-Castellón, E., Ania, C.O. (2019). Sunlight photoactivity of rice husks-derived biogenic silica. *Catalysis Today*, 328, 125-135. DOI: 10.1016/j.cattod.2018.12.008.

[82] Zeng, W., Bai, H. (2014). Swelling-agent-free synthesis of rice husk derived silica materials with large mesopores for efficient CO_2 capture. *Chemical Engineering Journal*, 251, 1-9. DOI: 10.1016/j.cej.2014.04.041.

[83] Tan, S.Y., Teh, C., Ang, C.Y., Li, M., Li, P., Korzh, V., Zhao, Y. (2017). Responsive mesoporous silica nanoparticles for sensing of hydrogen peroxide and simultaneous treatment toward heart failure. *Nanoscale*, 9(6), 2261. DOI: 10.1039/c6nr08869d.

[84] Vijayan, R., Kumar, G.S., Karunakaran, G., Surumbarkuzhali, N., Prabhu, S., Ramesh, R. (2020). Microwave combustion synthesis of tin oxide-decorated silica nanostructure using rice husk template for supercapacitor applications. *Journal of Materials Science: Materials in Electronics*, 31(7), 5738-5745. DOI: 10.1007/s10854-020-03142-y.

[85] Chowdhury, M.A. (2018). Silica Materials for Biomedical Applications in Drug Delivery, Bone Treatment or Regeneration, and MRI Contrast Agent. *Review Journal of Chemistry*, 8(2), 223-241. DOI: 10.1134/s2079978018020024.

[86] Prabha, S., Durgalakshmi, D., Rajendran, S., Lichtfouse, E. (2021). Plant-derived silica nanoparticles and composites for biosensors, bioimaging, drug delivery and supercapacitors: a review. *Environ. Chem. Lett.* 19, 1667-1691. DOI: 10.1007/s10311-020-01123-5.

[87] Umeda, J., Kondoh, K. (2010). High-purification of amorphous silica originated from rice husks by combination of polysaccharide hydrolysis and metallic impurities removal. *Industrial Crops and Products*, 32(3), 539-544. DOI: 10.1016/j.indcrop.2010.07.002.

[88] Xiong, Z., Li, T., Crosta, X. (2012). Cleaning of marine sediment samples for large diatom stable isotope analysis. *Journal of Earth Science*, 23(2), 161-172. DOI: 10.1007/s12583-012-0241-x.

[89] Madduluri, V.R., Mandari, K.K., Velpula, V., Varkolu, M., Kamaraju, S.R.R., Kang, M. (2020). Rice husk-derived carbon-silica supported Ni catalysts for selective hydrogenation of biomass-derived furfural and levulinic acid. *Fuel*, 261, 116339. DOI: 10.1016/j.fuel.2019.116339.

[90] Schneider, D., Wassersleben, S., Weiß, M., Denecke, R., Stark, A., Enke, D. (2020). A Generalized Procedure for the Production of High-Grade, Porous Biogenic Silica. *Waste and Biomass Valorization*, 11(1), 1-15. DOI: 10.1007/s12649-018-0415-6.

[91] Sprynskyy, M., Pomastowski, P., Hornowska, M., Król, A., Rafińska, K., Buszewski, B. (2017). Naturally organic functionalized 3D biosilica from diatom microalgae. *Materials and Design*, 132, 22-29. DOI: 10.1016/j.matdes.2017.06.044.

[92] Chandrasekhar, S., Pramada, P.N., Majeed, J. (2006). Effect of calcination temperature and heating rate on the optical properties and reactivity of rice husk ash. *Journal of Materials Science*, 41(23), 7926-7933. DOI: 10.1007/s10853-006-0859-0.

[93] Gong, Z., Wang, B., Chen, W., Ma, S., Jiang, W., Jiang, X. (2021). Waste straw derived Mn-doped carbon/mesoporous silica catalyst for enhanced low-temperature SCR of NO. *Waste Management*, 136, 28-35. DOI: 10.1016/j.wasman.2021.09.035.

[94] Habte, G.A., Bullo, T.A., Ahmed, Y. (2025). Statistical optimization characterizations and Eco- friendly synthesis of silica from sugarcane bagasse. *Scientific Reports*, 15(1), 8492. DOI: 10.1038/s41598-025-89366-6.

[95] Santana Costa, J.A., Paranhos, C.M. (2018). Systematic evaluation of amorphous silica production from rice husk ashes. *Journal of Cleaner Production*, 192, 688-697. DOI: 10.1016/j.jclepro.2018.05.028.

[96] Heo, J.N., Do, J.Y., Son, N., Kim, J., Kim, Y.S., Hwang, H., Kang, M. (2019). Rapid removal of methyl orange by a UV Fenton-like reaction using magnetically recyclable Fe-oxalate complex prepared with rice husk. *Journal of Industrial and Engineering Chemistry*, 70, 372-379. DOI: 10.1016/j.jiec.2018.10.038.

[97] Ghime, D., Ghosh, P. (2017). Heterogeneous Fenton degradation of oxalic acid by using silica supported iron catalysts prepared from raw rice husk. *Journal of Water Process Engineering*, 19, 156-163. DOI: 10.1016/j.jwpe.2017.07.025.

[98] Vu, A.T., Xuan, T.N., Lee, C.H. (2019). Preparation of mesoporous $Fe_2O_3 \cdot SiO_2$ composite from rice husk as an efficient heterogeneous Fenton-like catalyst for degradation of organic dyes. *Journal of Water Process Engineering*, 28, 169-180. DOI: 10.1016/j.jwpe.2019.01.019.

[99] Xiong, J., Li, G., Hu, C. (2020). Treatment of methylene blue by mesoporous Fe/SiO_2 prepared from rice husk pyrolytic residues. *Catal. Today,* 355, 529-538. DOI: 10.1016/j.cattod.2019.06.059

[100] Adam, F., Balakrishnan, S., Wong, P.-L. (2006). Rice Husk Ash Silica As a Support Material for Ruthenium Based Heterogenous Catalyst. *Journal of Physical Science*, 17(2), 1-13.

[101] Le, T.T., Pistidda, C., Nguyen, V.H., Singh, P., Raizada, P., Klassen, T., Dornheim, M. (2021). Nanoconfinement effects on hydrogen storage properties of MgH_2 and $LiBH_4$. *International Journal of Hydrogen Energy*, 46(46), 23723–23736. DOI: 10.1016/j.ijhydene.2021.04.150.

[102] Motomura, H., Mita, N., Suzuki, M. (2002). Silica accumulation in long-lived leaves of Sasa veitchii (Carrière) rehder (Poaceae-Bambusoideae). *Annals of Botany*, 90(1), 149-152. DOI: 10.1093/aob/mcf148.

[103] Fatimah, I., Rubiyanto, D., Taushiyah, A., Najah, F.B., Azmi, U., Sim, Y.-L. (2019). Use of ZrO_2 supported on bamboo leaf ash as a heterogeneous catalyst in microwave-assisted biodiesel conversion. *Sustainable Chemistry and Pharmacy*, 12, 100129. DOI: 10.1016/j.scp.2019.100129.

[104] Ma, J.F., Takahashi, E. (2002). Silicon-accumulating plants in the plant kingdom. In: *Soil, Fertilizer, and Plant Silicon Research in Japan,* 33, 63-71. DOI: 10.1016/b978-044451166-9/50005-1.

[105] Vanichvattanadecha, C., Singhapong, W., Jaroenworaluck, A. (2020). Different sources of silicon precursors influencing on surface characteristics and pore morphologies of mesoporous silica nanoparticles. *Applied Surface Science*, 513, 145568. DOI: 10.1016/j.apsusc.2020.145568.

[106] Ragni, R., Cicco, S.R., Vona, D., Farinola, G.M. (2018). Multiple Routes to Smart Nanostructured Materials from Diatom Microalgae: A Chemical Perspective. *Advanced Materials,* 30(19), 1704289. DOI: 10.1002/adma.201704289

[107] Yeh, Y.Q., Su, C.J., Wang, C.A., Lai, Y.C., Tang, C.Y., Di, Z., Frielinghaus, H., Su, A.C., Jeng, U.S., Mou, C.Y. (2021). Diatom-inspired self-assembly for silica thin sheets of perpendicular nanochannels. *Journal of Colloid and Interface Science*, 584, 647-659. DOI: 10.1016/j.jcis.2020.10.114.

[108] Monteiro, W.F., Diz, F.M., Andrieu, L., Morrone, F.B., Ligabue, R.A., Bernardo-Gusmão, K., de Souza, M.O., Schwanke, A.J. (2020). Waste to health: Ag-LTA zeolites obtained by green synthesis from diatom and rice-based residues with antitumoral activity. *Microporous and Mesoporous Materials*, 307, 110508. DOI: 10.1016/j.micromeso.2020.110508.

[109] Beidaghy Dizaji, H., Zeng, T., Hölzig, H., Bauer, J., Klöß, G., Enke, D. (2022). Ash transformation mechanism during combustion of rice husk and rice straw. *Fuel*, 307, 121768. DOI: 10.1016/j.fuel.2021.121768.

[110] Pasangulapati, V., Ramachandriya, K.D., Kumar, A., Wilkins, M.R., Jones, C.L., Huhnke, R.L. (2012). Effects of cellulose, hemicellulose and lignin on thermochemical conversion characteristics of the selected biomass. *Bioresource Technology*, 114, 663-669. DOI: 10.1016/j.biortech.2012.03.036.

[111] Gu, S., Zhou, J., Yu, C., Luo, Z., Wang, Q., Shi, Z. (2015). A novel two-staged thermal synthesis method of generating nanosilica from rice husk via pre-pyrolysis combined with calcination. *Industrial Crops and Products*, 65, 1-6. DOI: 10.1016/j.indcrop.2014.11.045.

[112] Liu, L., Ren, S., Yang, J., Jiang, D., Guo, J., Pu, Y., Meng, X. (2022). Experimental study on K migration, ash fouling/slagging behaviors and CO_2 emission during co-combustion of rice straw and coal gangue. *Energy*, 251, 123950. DOI: 10.1016/j.energy.2022.123950.

[113] Anuar, M.F., Fen, Y.W., Zaid, M.H.M., Matori, K.A., Khaidir, R.E.M. (2018). Synthesis and structural properties of coconut husk as potential silica source. *Results in Physics*, 11, 1-4. DOI: 10.1016/j.rinp.2018.08.018.

[114] Ghorbani, F., Younesi, H., Mehraban, Z., Çelik, M.S., Ghoreyshi, A.A., Anbia, M. (2013). Preparation and characterization of highly pure silica from sedge as agricultural waste and its utilization in the synthesis of mesoporous silica MCM-41. *Journal of the Taiwan Institute of Chemical Engineers*, 44(5), 821-828. DOI: 10.1016/j.jtice.2013.01.019.

[115] Liou, T.H., Yang, C.C. (2011). Synthesis and surface characteristics of nanosilica produced from alkali-extracted rice husk ash. *Materials Science and Engineering: B*, 176(7), 521-529. DOI: 10.1016/j.mseb.2011.01.007.