

Agricultural Waste- Derived Silica as a Sustainable Adsorbent for Water Purification: A Review

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Abstract: The increasing emphasis on sustainable technologies has encouraged the utilization of agricultural waste as a renewable source for the development of functional materials. Residues such as rice husk, wheat straw, sugarcane bagasse, and corn cob are rich in silica and can be converted into efficient adsorbents for wastewater remediation. This review discusses the extraction of silica from agricultural by-products using different approaches, including controlled combustion, acid-alkali treatment, and sol-gel synthesis, which significantly affect the structural, morphological, and surface properties of the final material. The obtained silica is generally amorphous and exhibits high porosity, large surface area, and abundant silanol groups, making it highly effective for the removal of heavy metals, dyes, and other hazardous pollutants from aqueous media. The adsorption process is influenced by several interactions, such as electrostatic attraction, hydrogen bonding, surface complexation, and ion exchange, depending on the nature of the adsorbent and solution conditions. Surface engineering strategies, including amine functionalization, metal oxide incorporation, and composite fabrication, have been explored to improve adsorption capacity and selectivity. Reported studies demonstrate that silica derived from agricultural residues can perform similarly to conventional commercial adsorbents while offering advantages related to low production cost, resource availability, and environmental sustainability. Although challenges associated with regeneration, consistency of raw materials, and industrial-scale implementation still need attention, biomass-derived silica represents a promising and environmentally responsible material for sustainable water treatment applications.

Keywords: Adsorption; Agricultural waste; Biosilica; Heavy metal removal; Rice husk ash; Water purification.

1. INTRODUCTION

The continuous expansion of agricultural activities across the globe has resulted in the generation of substantial quantities of agricultural residues, including rice husk, wheat husk, sugarcane bagasse, corn cob, and other crop by-products. In agrarian economies such as India, these residues are produced in large volumes during harvesting and processing operations. Conventional disposal methods, particularly open-field burning and uncontrolled dumping, contribute significantly to environmental pollution, including the release of particulate matter, greenhouse gases, and toxic emissions that adversely affect air quality and soil health (Green, 2019, 2019; Hamda et al., 2023; Loehr, 2012; Maji et al., 2020; Nagendran, 2011; Poggi-Varaldo, 1999; Rudoy et al., 2024). Consequently, the sustainable management and utilization of agricultural waste have become important priorities in environmental research and resource recovery.

At the same time, the availability of clean and safe water has emerged as a critical global concern. Industrial activities, especially those associated with mining, electroplating, textile processing, and chemical manufacturing, discharge wastewater containing heavy metals, dyes, and other hazardous organic compounds. These contaminants are often persistent, non-biodegradable, and capable of accumulating in living organisms, thereby posing serious risks to human health and ecological systems (Agarwal et al., 2022; Bhatnagar et al., 2013; Emenike et al., 2025; Khunt et al., 2019; Mo et al., 2018; Sharma et al., 2026). Conventional water treatment technologies such as chemical precipitation, membrane filtration, coagulation, and ion exchange are effective to some extent but are often associated with high operational costs,

energy requirements, and secondary waste generation. Among the various treatment methods, adsorption has been widely recognized as an efficient and versatile technique due to its simplicity, effectiveness, and ability to remove a wide range of pollutants; however, the high cost of commercial adsorbents such as activated carbon limits their widespread application, particularly in developing regions (Akhayere et al., 2019, 2022; Carraro et al., 2021; Gargiulo et al., 2024; Hamad et al., 2022; Khunt et al., 2019; Mo et al., 2018; Nordin et al., 2023; Okoro et al., 2022a, 2022b; Sharma et al., 2026; Sui et al., 2026; Taiye et al., 2024; Tan et al., 2008).

In recent years, considerable attention has been directed toward the development of low-cost and sustainable adsorbents derived from natural and waste materials. Agricultural residues have emerged as promising precursors for the synthesis of value-added materials due to their abundance, renewability, and chemical composition (Agarwal et al., 2022; Carraro et al., 2021; Gargiulo et al., 2024, 2024; Khunt et al., 2019; Mo et al., 2018; Sen, 2023; Sharma et al., 2026). Among these, silica derived from agricultural biomass has gained significant interest because of its favorable physicochemical properties, including high thermal stability, chemical inertness, and the presence of reactive surface functional groups. Rice husk, in particular, is one of the most extensively investigated sources of biogenic silica. It contains a high proportion of silica, which can be converted into rice husk ash containing approximately 70–95% SiO₂ through controlled combustion processes. The silica obtained under optimized conditions is predominantly amorphous, which is advantageous for adsorption applications due to its higher surface reactivity and greater availability of silanol (Si–OH) groups (Aharipour et al., 2022; Akhayere et al., 2022; Alhadhrami et al., 2022; El-Salamony et al., 2021a; Emenike et al., 2025; Jaturapiree et al., 2024; Kouadri et al., 2023; Kumalasari et al., 2024; Moayedi et al., 2019; Mor et al., 2016; Okoro et al., 2022a; Permatasari et al., 2016; Sawasdee et al., 2022; Seaf El-Nasr et al., 2021; Shukla, 2020; G. Singh et al., 2025; Yefremova et al., 2023).

The conversion of agricultural waste into silica represents an effective waste valorization strategy that aligns with the principles of green chemistry and circular economy. Various extraction and processing techniques, including acid leaching, alkali extraction, sol–gel processing, and controlled thermal treatment, have been employed to produce silica with tailored properties such as surface area, porosity, and particle size (Aharipour et al., 2022; Akhayere et al., 2019, 2022; Alhadhrami et al., 2022; Bakdash et al., 2020; Barani et al., 2024; El Bendary et al., 2021; El-Salamony et al., 2021b; Jaturapiree et al., 2024; Kouadri et al., 2023; Rakesh et al., 2024; Sawasdee et al., 2022; Shahbaz et al., 2023a; G. Singh et al., 2025; Taiye et al., 2024; Zawrah et al., 2021). These researches have demonstrated that silica derived from agricultural residues is effective in removing various pollutants from aqueous systems, including heavy metals such as lead, cadmium, chromium, and arsenic, as well as synthetic dyes and other organic contaminants.

The selection of appropriate processing conditions is crucial, as it directly influences the structural and functional characteristics of the resulting silica material. In addition to extraction methods, surface modification techniques such as amine functionalization and metal oxide incorporation have been explored to enhance the adsorption capacity and selectivity of biosilica toward specific contaminants. The adsorption process is governed by mechanisms such as surface complexation, electrostatic interactions, hydrogen bonding, and ion exchange, which depend on both the surface chemistry of the silica and the properties of the adsorbate.

Importantly, several studies have reported that biosilica exhibits adsorption performance comparable to that of commercial adsorbents, while offering significant advantages in terms of cost, availability, and environmental sustainability (Aharipour et al., 2022; Akhayere et al., 2019, 2022; Alhadhrami et al., 2022; Barani et al., 2024; Chanda et al., 2023; El Bendary et al., 2021; Hamad et al., 2022; Hegazi, 2013; Jaturapiree et al., 2024; Mustapha et al., 2023; Nordin et al., 2023; Rakesh et al., 2024; Sen, 2023, 2023; Shahbaz et al., 2023a; G. Singh et al., 2025, 2025; Sui et al., 2026).

Despite these advantages, certain challenges remain that limit the large-scale application of agricultural waste-derived silica. These include variability in feedstock composition, difficulties in achieving consistent material properties, limitations in regeneration and reuse, and challenges associated with scaling up production processes. Addressing these issues requires a comprehensive understanding of the relationships between raw material characteristics, processing methods, and adsorption performance.

In this context, the present review aims to provide a detailed and systematic overview of silica derived from agricultural biomass as an eco-friendly adsorbent for water purification. The review focuses on the sources of silica from different agricultural residues, extraction and processing techniques, characterization methods, adsorption mechanisms, and practical applications in water treatment. Additionally, the challenges and future prospects associated with the use of biosilica are discussed to highlight directions for further research and development in this field.

2. SOURCES OF SILICA FROM AGRICULTURAL WASTE

Agricultural residues are an abundant and renewable source of silica, as many plant species absorb silicon from the soil in the form of soluble silicic acid and subsequently deposit it within their tissues as hydrated amorphous silica. Upon thermal treatment, this biogenic silica can be recovered in a relatively pure form. However, the silica content and composition of agricultural waste vary depending on factors such as plant species, soil conditions, climate, and cultivation practices (Akhayere et al., 2019, 2022; Alhadhrami et al., 2022; El-Salamony et al., 2021a; Kouadri et al., 2023; Rakesh et al., 2024; G. Singh et al., 2025; Zawrah et al., 2021). Understanding the different sources of silica is essential for selecting suitable raw materials for the production of adsorbents.

Among various agricultural residues, rice husk is considered the most significant and widely studied source of silica. Rice husk constitutes approximately 20 wt% of the total rice grain and is generated in large quantities during rice milling processes. When subjected to controlled combustion, rice husk produces rice husk ash (RHA), which typically contains about 70–95 wt% silica, depending on combustion temperature and pretreatment conditions. The silica present in RHA is predominantly amorphous when the combustion temperature is maintained below approximately 800 °C, which is advantageous for adsorption applications due to its high surface reactivity and abundance of silanol groups. Because of these properties, rice husk has been extensively utilized as a precursor for the synthesis of biosilica in water purification studies.

Another important agricultural residue is sugarcane bagasse, which is generated after the extraction of juice in sugar industries. Bagasse is primarily composed of cellulose, hemicellulose, and lignin, with a relatively lower inorganic content compared to rice husk. Upon combustion, sugarcane bagasse ash typically contains 60–75 wt% silica, along with other oxides such as alumina, iron oxide, and calcium oxide. Although the silica content is lower than that of rice husk, bagasse-derived silica is still considered a viable alternative due to its widespread availability, particularly in sugar-producing regions (Bortolotto Teixeira et al., 2021; Habte et al., 2025; Mohd et al., 2017; Ni'mah et al., 2023; September et al., 2023a). However, additional purification steps, such as acid leaching, are often required to improve the silica quality.

Wheat husk and wheat straw are also significant agricultural residues, especially in regions where wheat is a major crop. The silica content in wheat-derived ash is generally reported to be in the range of 50–65 wt%, along with notable amounts of alkali metals such as potassium and calcium. The presence of these impurities can influence the properties of the resulting silica, particularly its crystallinity and surface area. Nevertheless, with appropriate pretreatment and controlled processing, wheat residues can be converted into functional silica materials suitable for adsorption applications (Akhayere et al., 2019; Dodson, 2011; Shaikh et al., 2013; Terzioglu et al., 2013; Terzioglu et al., 2019).

In addition to these, corn cob and maize residues represent other potential sources of silica. Corn cob ash typically contains 45–60 wt% silica, depending on the cultivation and processing conditions. Although the silica content is comparatively lower than that of rice husk, these materials are readily available in many agricultural regions and can be utilized as alternative feedstocks for silica production. Research efforts have focused on improving extraction efficiency from such residues through chemical treatments and optimized thermal processes (Adebisi et al., 2020; Balasubramaniam et al., 2020; Okoronkwo et al., 2013; Sulaiman et al., 2022; Velmurugan et al., 2015).

A comparative evaluation of agricultural wastes indicates that rice husk remains the most favorable source of silica in terms of yield, purity, and ease of processing. However, the utilization of other residues such as sugarcane bagasse, wheat straw, and corn cob is gaining attention due to regional availability and the need for comprehensive waste management strategies. Importantly, the silica obtained from these sources is generally amorphous and contains surface functional groups that are beneficial for adsorption processes.

The selection of agricultural waste as a silica source should therefore consider not only the silica content but also factors such as local availability, cost of processing, and environmental impact. Efficient utilization of these residues not only provides a low-cost raw material for adsorbent preparation but also contributes to sustainable waste management and environmental protection.

3. EXTRACTION AND PROCESSING OF SILICA FROM AGRICULTURAL WASTE

The extraction of silica from agricultural residues involves the conversion of biogenic silica embedded within plant tissues into a usable and relatively pure inorganic form. The physicochemical properties of the extracted silica, including its purity, surface area, porosity, and crystallinity, are strongly influenced by the processing method and operational conditions. Therefore, the selection of appropriate extraction and processing techniques is critical for obtaining silica materials suitable for adsorption-based water purification applications.

3.1 THERMAL TREATMENT (CONTROLLED COMBUSTION)

Thermal treatment is the most commonly employed method for the initial conversion of agricultural waste into silica-rich ash. In this process, biomass is subjected to controlled combustion to remove organic constituents such as cellulose, hemicellulose, and lignin, leaving behind inorganic residues primarily composed of silica. The combustion temperature plays a crucial role in determining the structural characteristics of the resulting silica.

Studies have shown that combustion in the temperature range of 500–700 °C produces predominantly amorphous silica, which is highly desirable for adsorption applications due to its higher surface reactivity and greater availability of silanol groups (Aharipour et al., 2022; Barani et al., 2024; Carraro et al., 2021; Falk et al., 2019; Farirai et al., 2021a; Hamidu et al., 2025; Mohd et al., 2017; Piela et al., 2020; September et al., 2023a, 2023b; Shahbaz et al., 2023b). When the combustion temperature exceeds approximately 800 °C, the amorphous silica tends to undergo phase transformation into crystalline forms such as cristobalite and tridymite. These crystalline phases exhibit lower surface area and reduced adsorption capacity, making them less suitable for water purification applications. Therefore, controlled low-temperature combustion is generally preferred for producing high-quality biosilica.

3.2 ACID LEACHING PRE-TREATMENT

Acid leaching (Pa et al., 2013) is widely used as a pre-treatment step to remove metallic impurities such as potassium, calcium, magnesium, and iron, which are naturally present in agricultural residues. These impurities can interfere with the formation of amorphous silica during combustion and may reduce the adsorption efficiency of the final product.

Dilute mineral acids such as hydrochloric acid, nitric acid, or sulfuric acid are typically used for this purpose. Acid pre-treatment has been shown to enhance the purity of silica by dissolving alkali and alkaline earth metals, thereby preventing undesirable reactions that may lead to silica crystallization. In the case of rice husk, acid-leached samples consistently produce ash with higher silica content and improved surface properties compared to untreated biomass. However, excessive acid concentration or prolonged treatment may lead to partial dissolution of silica, which should be carefully controlled.

3.3 ALKALI EXTRACTION AND PRECIPITATION

Alkali extraction is one of the most effective methods for producing high-purity silica from agricultural ash (Farirai et al., 2021a; Harun et al., 2024; Kouadri et al., 2023; Okoronkwo et al., 2013; Seghir et al., 2023; September et al., 2023a). In this process, silica present in the ash is dissolved in an alkaline medium, typically sodium hydroxide or potassium hydroxide, to form soluble silicate species. The resulting silicate solution is then neutralized using an acid, leading to the precipitation of hydrated silica.

This method allows better control over the purity, particle size, and surface properties of the final silica product (Kamari and Ghorbani, 2021). The precipitation conditions, such as pH, temperature, and rate of acid addition, significantly influence the structure and morphology of the silica obtained. Although alkali extraction produces high-quality silica, it involves multiple processing steps and generates alkaline waste streams that require proper treatment before disposal.

3.4 SOL-GEL PROCESSING

Sol-gel processing is an advanced method used for the synthesis of nanoscale silica with controlled structural properties (Adebisi et al., 2020; Ni'mah et al., 2023; Okoronkwo et al., 2013). In this approach, silicate precursors obtained from agricultural waste are subjected to hydrolysis and condensation reactions, resulting in the formation of a three-dimensional silica network.

Silica produced via the sol-gel method typically exhibits high surface area, uniform pore distribution, and controlled particle size, making it particularly suitable for adsorption applications. This method also allows the incorporation of functional

groups or dopants during synthesis, enabling the preparation of modified silica with enhanced adsorption performance. However, sol-gel processing requires careful control of parameters such as pH, temperature, and aging time, and may involve higher processing costs compared to simpler methods.

3.5 INFLUENCE OF PROCESSING PARAMETERS

The characteristics of agricultural waste-derived silica are highly sensitive to processing conditions such as temperature, heating rate, acid or alkali concentration, and reaction time. Lower combustion temperatures favour the formation of amorphous silica, while optimized leaching conditions improve purity without significantly affecting yield.

Similarly, the conditions used during alkali extraction and precipitation determine the particle size, surface area, and porosity of the resulting silica. Studies (Farirai et al., 2021b; Kesari et al., 2017; Rudoy et al., 2024; Seghir et al., 2023; Taiye et al., 2024) have emphasized that no single method is universally optimal; instead, the choice of extraction technique should be guided by the intended application of the silica material. For water purification applications, methods that produce high surface area and amorphous structure are generally preferred.

4. CHARACTERIZATION OF AGRICULTURAL WASTE-DERIVED SILICA

Characterization of silica derived from agricultural residues is essential to understand its structural, morphological, and surface properties, which directly influence its adsorption performance in water purification applications. The physicochemical characteristics of biosilica vary depending on the source material and processing conditions. A combination of analytical techniques is generally employed to evaluate crystallinity, functional groups, morphology, surface area, and elemental composition.

4.1 CRYSTALLINITY AND PHASE IDENTIFICATION (X-RAY DIFFRACTION ANALYSIS)

X-ray diffraction (Meftah et al., 2023; Naddaf et al., 2020; Okoronkwo et al., 2013; Ramasamy et al., 2023; Terzioglu et al., 2013; Velmurugan et al., 2015) (XRD) is widely used to determine the structural nature of silica obtained from agricultural waste. Silica derived from biomass is typically amorphous when produced under controlled combustion conditions below approximately 700–800 °C. This amorphous structure is identified by a broad diffraction peak centered around $2\theta \approx 22^\circ$, which corresponds to disordered silica networks. When combustion temperature increases beyond this range, the silica may transform into crystalline phases such as cristobalite or tridymite. These crystalline forms exhibit sharp diffraction peaks and generally possess lower surface reactivity and reduced adsorption capacity. Therefore, maintaining an amorphous structure is crucial for achieving effective adsorption performance.

4.2 SURFACE FUNCTIONAL GROUPS (FOURIER TRANSFORM INFRARED SPECTROSCOPY)

Fourier transform infrared (FTIR) spectroscopy (Ghorbani et al., 2013; Meftah et al., 2023; Okoronkwo et al., 2013; Terzioglu et al., 2013; Velmurugan et al., 2015) is used to identify functional groups present on the silica surface. Typical FTIR spectra of agricultural waste-derived silica exhibit a strong absorption band in the region of 1080–1100 cm^{-1} , corresponding to the asymmetric stretching vibration of Si–O–Si bonds. Additional bands near 800 cm^{-1} and 460 cm^{-1} are associated with symmetric stretching and bending vibrations, respectively. A broad absorption band in the region of 3200–3600 cm^{-1} is attributed to the presence of surface silanol (Si–OH) groups and adsorbed water molecules. These silanol groups play a key role in adsorption processes, as they act as active sites for interaction with metal ions and organic pollutants. Changes in FTIR spectra after adsorption provide evidence of chemical interaction between the silica surface and the adsorbate.

4.3 MORPHOLOGY AND PARTICLE SIZE (SEM AND TEM ANALYSIS)

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are commonly used to examine the morphology and microstructure of biosilica (Kouadri et al., 2023; Naddaf et al., 2020; Ramasamy et al., 2023; Vaibhav et al., 2015; Velmurugan et al., 2015). SEM images generally reveal irregular, porous, and heterogeneous structures, reflecting the natural composition of the biomass and the removal of organic components during thermal treatment (Moayedhi et al., 2019).

TEM analysis of silica obtained through chemical extraction or sol-gel methods often shows nanoscale particles with relatively uniform size distribution, typically in the range of 20–100 nm. The porous and nanoscale structure contributes to increased surface area and enhances adsorption efficiency by providing more active sites.

4.4 SURFACE AREA AND POROSITY (BET ANALYSIS)

Surface area and pore structure are critical parameters influencing the adsorption capacity of silica. The Brunauer–Emmett–Teller (BET) method is commonly used to determine the specific surface area of biosilica (Dorairaj et al., 2022; Permatasari et al., 2016; Rovani et al., 2018). Agricultural waste-derived silica typically exhibits surface areas in the range of 50–300 m² g⁻¹, depending on the extraction method and processing conditions.

Silica produced through alkali extraction and sol–gel methods generally shows higher surface area and well-developed porosity compared to directly combusted ash. The pore structure is often mesoporous, which is favourable for the adsorption of heavy metal ions and organic molecules from aqueous solutions. Higher surface area and appropriate pore size distribution significantly enhance adsorption performance.

4.5 ELEMENTAL COMPOSITION AND PURITY

Elemental composition of biosilica is typically analyzed using techniques such as energy-dispersive X-ray spectroscopy (EDX) or X-ray fluorescence (XRF) (Kouadri et al., 2023; Meftah et al., 2023; Sulaiman et al., 2022; Vaibhav et al., 2015). These analyses confirm that silica (SiO₂) is the dominant component, while minor amounts of impurities such as potassium, calcium, magnesium, and iron may be present depending on the raw material and processing method. Acid leaching significantly reduces the concentration of these impurities, resulting in higher purity silica with improved adsorption characteristics. High purity is particularly important for ensuring reproducibility and minimizing interference during adsorption processes.

5. ADSORPTION MECHANISMS AND MODIFICATION STRATEGIES

The adsorption performance of agricultural waste-derived silica is governed by its surface chemistry, structural properties, and interaction with the target pollutants. Understanding the adsorption mechanism is essential for optimizing silica-based materials for water purification applications. In most cases, adsorption onto biosilica involves a combination of physical and chemical interactions, rather than a single dominant mechanism.

5.1 ROLE OF SURFACE SILANOL GROUPS

Silica surfaces are characterized by the presence of silanol (Si–OH) groups, which play a crucial role in adsorption processes (Mustapha et al., 2023; Rovani et al., 2018; Sarma et al., 2022; Sen, 2023; Sui et al., 2026; Taiye et al., 2024). These functional groups act as active sites for interaction with pollutants and are responsible for the hydrophilic nature of silica. Depending on the pH of the solution, silanol groups can undergo protonation or deprotonation, thereby influencing the surface charge and adsorption behavior.

At lower pH values, the silica surface tends to be positively charged due to protonation of silanol groups, which facilitates the adsorption of anionic species. In contrast, at higher pH values, deprotonation results in a negatively charged surface, promoting the adsorption of cationic metal ions such as Pb²⁺, Cd²⁺, and Cu²⁺ through electrostatic attraction and surface complexation. This pH-dependent behavior is a key factor in determining the efficiency of adsorption processes (Mustapha et al., 2023; Sui et al., 2026).

5.2 ADSORPTION MECHANISMS

The adsorption of contaminants onto agricultural waste-derived silica generally occurs through multiple mechanisms (Barani et al., 2024; Emenike et al., 2025; Hamad et al., 2022; Mo et al., 2018; Mustapha et al., 2023; Rovani et al., 2018; Sen, 2023; Sharma et al., 2026; Yefremova et al., 2023), including:

- **Surface complexation:** Metal ions form coordinate bonds with oxygen atoms of silanol groups, resulting in the formation of surface complexes. This mechanism is particularly important for heavy metal adsorption.
- **Electrostatic interaction:** Charged pollutants are attracted to oppositely charged silica surfaces. This mechanism is highly dependent on pH and ionic strength of the solution.

- **Ion exchange:** Exchange of ions between the silica surface and the solution, especially in the presence of alkali metal ions associated with the silica structure.
- **Hydrogen bonding:** Interaction between silica surface groups and polar functional groups present in organic pollutants such as dyes.

These mechanisms often operate simultaneously, contributing to the overall adsorption capacity of biosilica. Spectroscopic studies, particularly FTIR analysis, frequently show changes in peak positions after adsorption, confirming the involvement of surface functional groups in pollutant binding (Morales-Paredes et al., 2023; Prempeh et al., 2021; Rakesh et al., 2024; Velmurugan et al., 2015).

5.3 SURFACE MODIFICATION OF SILICA

Although unmodified silica exhibits significant adsorption capacity, surface modification is commonly employed to enhance its performance. Chemical functionalization introduces additional active sites and improves selectivity toward specific contaminants.

One of the most widely used modification techniques (Araghi et al., 2015; Beagan et al., 2022; Bouazizi et al., 2022; Cashin et al., 2018; Fan et al., 2022; Lashaki et al., 2019; Li et al., 2021) is amine functionalization, where organosilane compounds such as 3-aminopropyltriethoxysilane (APTES) are grafted onto the silica surface. The introduction of amine groups increases the affinity of silica toward heavy metal ions through chelation and electrostatic interactions, resulting in improved adsorption capacity.

5.4 METAL OXIDE-LOADED AND COMPOSITE MATERIALS

Another effective strategy involves the incorporation of metal oxides such as iron, manganese, or aluminum oxides onto the silica surface (Arrisujaya et al., 2025; Dave et al., 2014; Khunt et al., 2019; Neyaz et al., 2014; Rasalingam et al., 2014; Saad Algarni et al., 2022; Saraswathi et al., 2019; Zeng, 2003). These composites combine the high surface area of silica with the strong adsorption affinity of metal oxides, particularly for contaminants such as arsenic and chromium.

Iron oxide-modified silica has been reported to exhibit enhanced adsorption of arsenic species due to specific surface complexation mechanisms. Similarly, silica-based composites (Saraswathi et al., 2019; Zawrah et al., 2021) with other functional materials have been developed to improve adsorption efficiency and mechanical stability. Such modifications also facilitate easier separation of the adsorbent from treated water, especially when magnetic particles are incorporated.

5.5 INFLUENCE OF SOLUTION CONDITIONS

The efficiency of adsorption is strongly influenced by parameters such as pH, contact time, initial pollutant concentration, and temperature (Ali, 2012; Bonilla-Petriciolet et al., 2017; Clifford et al., 1986; Mo et al., 2018; Shukla, 2020). Among these, pH plays a particularly important role, as it affects both the surface charge of silica and the speciation of pollutants in solution. Most studies report that adsorption of heavy metals is more favorable in slightly acidic to neutral pH conditions, where electrostatic attraction and surface complexation are optimized. Contact time studies typically show rapid initial adsorption followed by slower uptake as equilibrium is approached. This behavior reflects the availability of active sites and diffusion of pollutants into porous structures.

6. APPLICATIONS OF AGRICULTURAL WASTE-DERIVED SILICA IN WATER PURIFICATION

Agricultural waste-derived silica has been widely investigated as an effective adsorbent for water purification due to its high surface area, porous structure, and chemically active surface. The presence of silanol groups and tunable surface properties allows silica to interact with a variety of pollutants present in water. Applications of biosilica (Agarwal et al., 2022; Arrisujaya et al., 2025; Bonilla-Petriciolet et al., 2017; Desobgo, 2024; Emenike et al., 2025; Goswami et al., 2022; Khunt et al., 2019, 2019; Kumalasari et al., 2024; Mor et al., 2016; Okoro et al., 2022a; Seaf El-Nasr et al., 2021; Sen, 2023; Sharma et al., 2026; Sui et al., 2026; Taiye et al., 2024) mainly focus on the removal of heavy metal ions, dyes, and other organic contaminants from aqueous systems.

6.1 REMOVAL OF HEAVY METAL IONS

Heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), chromium (Cr^{6+}/Cr^{3+}), copper (Cu^{2+}), and arsenic species are among the most harmful water pollutants due to their toxicity, persistence, and ability to bioaccumulate. Silica derived from agricultural waste has demonstrated strong adsorption capability for these metal ions (Hegazi, 2013; Kumalasari et al., 2024; Okoro et al., 2022b; Paranjape et al., 2023; Sui et al., 2026; Yefremova et al., 2023).

The adsorption of heavy metals onto biosilica occurs primarily through surface complexation and electrostatic interaction with silanol groups. The efficiency of adsorption is strongly dependent on pH, as it influences both the surface charge of silica and the speciation of metal ions. Studies have shown that maximum adsorption of cationic metals generally occurs at near-neutral pH conditions, where deprotonated silanol groups enhance metal binding. Chemical modification of silica significantly improves its adsorption capacity. For example, amine-functionalized silica derived from rice husk has been reported to exhibit enhanced removal of Pb^{2+} and Cd^{2+} due to the formation of stable metal–amine complexes (Beagan et al., 2022; Bouazizi et al., 2022; Fan et al., 2022; Lashaki et al., 2019). Similarly, silica modified with iron oxide shows improved adsorption of arsenic species through specific surface interactions (Arrisujaya et al., 2025; Dave et al., 2014; Mustapha et al., 2023; Rasalingam et al., 2014).

6.2 REMOVAL OF DYES AND ORGANIC POLLUTANTS

In addition to heavy metals, agricultural waste-derived silica has been applied for the removal of synthetic dyes, which are commonly discharged from textile, paper, and dyeing industries (El Bendary et al., 2021; Jaturapiree et al., 2024; Wang et al., 2020). Dyes such as methylene blue, methyl orange, and rhodamine B are frequently used as model pollutants in adsorption studies.

The adsorption of dyes onto silica is governed by electrostatic attraction, hydrogen bonding, and physical adsorption within the porous structure of the material. Cationic dyes are generally more effectively adsorbed due to electrostatic attraction with negatively charged silica surfaces at higher pH values. The porous nature of biosilica also facilitates diffusion of dye molecules into internal adsorption sites, enhancing overall removal efficiency (Bharathi et al., 2013; Birniwa et al., 2022; Chinedu Egbosiuba, 2022; Jaturapiree et al., 2024).

Modified silica materials often exhibit improved adsorption performance compared to unmodified biosilica. Functionalization introduces additional binding sites and enhances interaction with dye molecules, resulting in higher adsorption capacity and faster kinetics.

6.3 COMPARATIVE PERFORMANCE WITH COMMERCIAL ADSORBENTS

Comparative studies have shown that agricultural waste-derived silica can perform competitively with conventional adsorbents such as commercial silica and activated carbon, particularly for the removal of heavy metals. While activated carbon typically exhibits higher adsorption capacity for certain organic pollutants, biosilica offers several advantages, including lower cost, abundance, and ease of preparation (Ali, 2012; Goswami et al., 2022; Hamad et al., 2022; Kesari et al., 2017; Nordin et al., 2023; Okoro et al., 2022a; Rakesh et al., 2024; J. Singh et al., 2020).

Furthermore, the adsorption performance of biosilica can be tailored through surface modification and optimization of processing conditions, allowing it to approach or match the efficiency of commercial materials for specific applications.

6.4 REGENERATION AND REUSABILITY

The practical application of adsorbents depends not only on their adsorption capacity but also on their ability to be regenerated and reused. Agricultural waste-derived silica can generally be regenerated using simple desorption agents such as dilute acids or bases. Studies indicate that biosilica retains a significant portion of its adsorption capacity after multiple adsorption–desorption cycles, although a gradual decline is often observed due to incomplete desorption or structural changes (Akhayere et al., 2019; Bindra et al., 2022). Surface-modified silica may exhibit stronger binding with pollutants, which can affect regeneration efficiency. Further research is required to develop efficient regeneration techniques and to evaluate the long-term stability of biosilica under repeated use.

7. CHALLENGES, LIMITATIONS, AND FUTURE OUTLOOK

Although agricultural waste-derived silica has demonstrated significant potential as an eco-friendly adsorbent for water purification, several scientific, technical, and practical challenges must be addressed before its large-scale application can be realized. These challenges are primarily associated with variability in raw materials, processing limitations, regeneration efficiency, and scale-up feasibility.

7.1 VARIABILITY IN FEEDSTOCK COMPOSITION

One of the major limitations in the utilization of agricultural waste as a source of silica is the inherent variability in feedstock composition. The silica content, as well as the presence of impurities such as alkali and alkaline earth metals, depends on factors including plant species, soil composition, climatic conditions, and agricultural practices. As a result, even the same type of biomass, such as rice husk, may exhibit variations in silica yield and purity across different regions or harvesting periods. This variability can lead to inconsistencies in the physicochemical properties of the extracted silica, affecting parameters such as surface area, porosity, and adsorption performance. For practical applications, it is essential to develop standardized pre-treatment and processing protocols to ensure reproducibility and consistent material quality.

7.2 PROCESSING CHALLENGES AND ENVIRONMENTAL CONCERNS

Although the conversion of agricultural waste into silica supports waste valorization, some extraction methods involve chemical treatments that may pose environmental concerns. Acid leaching and alkali extraction processes generate secondary waste streams that require proper neutralization and disposal (Khunt et al., 2019; Kouadri et al., 2023; Maji et al., 2020; Pa et al., 2013). If not managed appropriately, these processes may offset some of the environmental benefits associated with the use of waste-derived materials. In addition, thermal treatment requires energy input, and uncontrolled combustion can result in the formation of crystalline silica phases, which are less desirable for adsorption applications. Therefore, optimizing processing conditions to minimize chemical usage and energy consumption remains an important area of research.

7.3 REGENERATION AND REUSABILITY LIMITATIONS

The regeneration and reuse of adsorbents are critical factors for their economic and practical viability. While agricultural waste-derived silica can be regenerated using chemical desorption methods, a gradual decrease in adsorption capacity is often observed over repeated cycles. This decline may be attributed to incomplete removal of adsorbed pollutants, structural changes in the silica matrix, or loss of active surface functional groups. Surface-modified silica, although exhibiting higher adsorption efficiency, may show reduced regeneration performance due to stronger binding interactions between the adsorbent and the pollutant. Therefore, developing efficient and sustainable regeneration strategies remains a key challenge.

7.4 SCALE-UP AND REAL-WORLD APPLICATION

Most studies on agricultural waste-derived silica are conducted at laboratory scale using synthetic solutions under controlled conditions. However, real wastewater systems are more complex and contain a mixture of contaminants, competing ions, and variable pH conditions. These factors can significantly influence adsorption performance and may reduce efficiency compared to laboratory results.

Scaling up the production of biosilica also requires consideration of factors such as raw material availability, process cost, energy consumption, and integration with existing water treatment systems. Issues related to handling, separation, and disposal of spent adsorbents must also be addressed to ensure practical feasibility.

7.5 FUTURE RESEARCH DIRECTIONS

Future research should focus on the development of environmentally friendly and cost-effective extraction methods that minimize chemical usage and energy consumption. Green synthesis approaches, including low-temperature processing and solvent-efficient techniques, are expected to play an important role in improving the sustainability of biosilica production.

Further investigation into the relationship between processing conditions, structural properties, and adsorption performance is necessary to optimize material design. Advanced surface modification strategies, including the development of hybrid and multifunctional materials, may enhance selectivity and reusability.

Importantly, more studies are required to evaluate the performance of agricultural waste-derived silica under real wastewater conditions and at pilot or industrial scale. Such efforts will help bridge the gap between laboratory research and practical application, enabling the wider adoption of biosilica in water purification systems.

8. CONCLUSION

Silica derived from agricultural biomass has emerged as a promising and sustainable material for water purification applications. The abundance of agricultural residues such as rice husk, wheat straw, sugarcane bagasse, and corn cob provides an opportunity to convert low-value waste into functional materials with significant environmental benefits. The high silica content of these residues, combined with their ability to yield predominantly amorphous silica with reactive surface silanol groups, makes them particularly suitable for adsorption-based removal of pollutants.

The present review highlights that the properties of agricultural waste-derived silica are strongly influenced by the nature of the raw material as well as the extraction and processing methods employed. Techniques such as controlled thermal treatment, acid leaching, alkali extraction, and sol-gel processing enable the production of silica with tailored structural and surface characteristics. These properties, including surface area, porosity, and functional group availability, play a critical role in determining adsorption performance.

It has been observed that biosilica exhibits considerable efficiency in the removal of heavy metals and synthetic dyes from aqueous systems. The adsorption process involves multiple mechanisms, including surface complexation, electrostatic interactions, ion exchange, and hydrogen bonding, which depend on solution conditions such as pH and pollutant concentration. Furthermore, surface modification strategies, including amine functionalization and metal oxide incorporation, significantly enhance the adsorption capacity and selectivity of silica toward specific contaminants.

Despite these advantages, several challenges remain that must be addressed for the practical implementation of agricultural waste-derived silica. Variability in feedstock composition, limitations in regeneration efficiency, and challenges associated with large-scale production and real wastewater treatment systems require further investigation. Addressing these issues will be essential to ensure consistent material performance and economic feasibility.

Future research should focus on developing environmentally sustainable processing methods, improving regeneration and reuse strategies, and evaluating the performance of biosilica under realistic operating conditions. With continued advancements in material design and process optimization, agricultural waste-derived silica has the potential to become an effective and widely adopted solution for sustainable water purification and environmental protection.

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