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SYNTHESIS APPROACHES AND APPLICATIONS OF SILICON NANOPARTICLES FROM AGRICULTURAL WASTES: A REVIEW

Aleena Elizabath Mathew
Student, MSc Chemistry, Christ University, Bangalore

ABSTRACT

This concise review provides an overview of silicon nanoparticle (Si NP) synthesis techniques using agricultural waste sources like rice husks, sugarcane bagasse, and wheat straw. It covers various methods, including thermal reduction, sol-gel, microemulsion, and laser ablation. The paper highlights Si NPs' versatile applications in biomedicine, energy storage, agriculture, environmental remediation, electronics, and optoelectronics, with a focus on sustainability. Additionally, it identifies research gaps in the field, emphasizing the need for improved synthesis efficiency and expanded application domains. This review offers valuable insights into the potential of agricultural waste for Si NP production and its profound impact across diverse industries.

1.INTRODUCTION

This brief overview emphasizes the increasing importance of Si NPs as a result of their distinct characteristics and extensive array of uses. It focuses on the synthesis techniques of Si NPs using agricultural waste materials like rice husks, sugarcane bagasse, and wheat straw, offering an eco-friendly and resource-efficient approach. The review comprehensively covers various synthesis methods, including thermal reduction, sol-gel, microemulsion, and laser ablation, showcasing the versatility of Si NP production. This diversity enables tailoring Si NPs for specific uses, making them promising materials across multiple industries. The central theme revolves around the manifold applications of Si NPs in biomedicine, energy storage, agriculture, environmental remediation, electronics, and optoelectronics. This demonstrates their potential to address diverse challenges while promoting sustainability. Additionally, the review identifies research gaps, emphasizing the need for improved synthesis efficiency and exploration of new application areas, paving the way for further innovation. In summary, this review underscores the significance of Si NP synthesis from agricultural waste, emphasizing their transformative impact on various industries. Si NPs offer a sustainable route to nanomaterial production, making this review a valuable resource for researchers and stakeholders interested in harnessing their potential.

2. DIFFERENT GREEN SOURCES OF SILICON NANOPARTICLES

Si NPs possess unique properties that make them promising materials for a wide range of applications, spanning from biomedical sciences to electronics. These properties include high surface area, biocompatibility, stability, surface reactivity, and tunable pore size [1]. Synthesizing Si NPs from agricultural waste materials represents an innovative and sustainable approach, aligning with principles of green chemistry and sustainability. Agricultural waste, such as rice hulls [2], bamboo leaves, sugarcane bagasse [3], and rice straw [4], can serve as cost-effective precursors for Si NP production, taking advantage of their abundant availability at the end of each harvest season. Notably, a study by Sivakumar and colleagues introduced a unique approach, synthesizing pure silica from waste materials like cow dung ash using the sol-gel process, resulting in Si NPs with 100% purity and a spherical shape, demonstrating the potential of agricultural waste materials in creating high-quality Si NPs [5].

Gonzalez and colleagues developed a unique method for creating crystalline Si NPs by bioprocessing agricultural waste using annelids (Eisenia foetida) and subsequent calcination and acid treatment [6]. Sorghum bicolor residues, rich in silica, were used by Athinarayan et al. to synthesize Si NPs for potential food industry applications [7]. Balamurugan and team synthesized nanosilica from Sorghum vulgare seed heads [8]. Gurbani et al. introduced an innovative method using sedge (Carex riparia weed) waste to produce Si NPs sustainably [9]. Wassie and collaborators synthesized nanosilica from Tef straw through heat and acid treatment in Ethiopia [10]. These agricultural waste materials offer a valuable resource for Si NP synthesis, with various methods such as sol-gel, microemulsion, thermal reduction, laser ablation, and chemical reduction being employed. Si NPs derived from agricultural waste find versatile applications in biomedicine [11], energy storage [12], agriculture [13], environmental remediation [14], electronics, and optoelectronics [15]. This review provides an overview of these synthesis methods and highlights the wide-ranging applications of Si NPs from agricultural waste sources.

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Sl.no	Agricultural Waste Material	Reference
1	Rice Hull	[2]
2	Bamboo leaves	[3]
3	Sugarcane bagasse	[3]
4	Rice Straw	[4]
5	Cow dung ash	[5]
6	Agricultural waste using species Eisenia foetida	[6]
7	Sorghum bicolor	[7]
8	Sorghum vulgare seed heads	[8]
9	Sedge-specifically the Carex riparia weed	[9]
10	Tef straw	[10]

Table 1- This table summarizes different source of Si NPs

3. VARIOUS SYNTHESIS APPROACHES OF SILICON NANOPARTICLES

The synthesis of Si NPs from agricultural waste involves collecting and preparing the waste materials, extracting silicon, and converting it into nanoparticles. Several methods, including thermal reduction [16], sol-gel [17], microemulsion [18], and laser ablation [19], are employed, chosen based on the specific agricultural byproduct and desired nanoparticle properties. These methods offer versatile approaches to utilize agricultural waste for Si NP production.

3.1. Thermal Reduction

Thermal reduction is a cost-effective method for producing Si NPs from agricultural waste like rice husks. This process involves pyrolyzing the waste at high temperatures to yield amorphous silica, which is then reduced to Si NPs through carbothermal or magnesiothermic reduction. Researchers, including Weixing Wang and colleagues, have successfully produced biogenic Si NPs from rice husks using controlled pyrolysis. Optimal conditions were found at 700°C for two hours, resulting in Si NPs measuring approximately 20-30 nanometers (nm) in diameter. Potassium ions present in rice husks acted as catalysts for silica transformation, resulting in high-purity amorphous Si NPs with a narrow size distribution suitable for various applications [16].

3.2. Sol-Gel Method

The sol-gel method involves dissolving agricultural waste-derived silica in a solvent, followed by controlled hydrolysis and condensation to produce Si NPs with precise control over size and surface properties. Farook Adam and colleagues used rice husk as a template-free source to synthesize mesoporous Si NPs under ambient conditions. Transmission electron microscopy confirmed the formation of spherical Si NPs with an average size of 50.9 nm and a specific surface area. These Si NPs exhibit a narrow range of pore sizes, making them promising for various applications [17].

3.3. Microemulsion Technique

The microemulsion method utilizes agricultural byproducts to create micelles, acting as nanoreactors for the formation of uniform Si NPs. This approach involves the formation of either oil-in-water (O/W) or water-in-oil (W/O) micelles stabilized by surfactants. The resulting SiNP size is mainly determined by the nanoreactor volume, where silica precursors undergo hydrolysis and condensation reactions, yielding monodisperse Si NPs [18].

3.4. Laser Ablation

Laser ablation is employed to produce Si NPs directly from agricultural waste-derived silica, offering precise control over particle size and shape. In a study utilizing raw sugarbeet bagasse as the target, a commercial nanosecond pulsed Nd:YLF laser was used to generate SiNPs in a water medium. The laser ablation caused changes in color and fiber damage in the bagasse, which were then removed from the NP solution through filtration. The process involved placing bagasse in water, focusing the laser beam on the target, and scanning it for about 5 minutes. This resulted in the formation of Si NPs, which were separated from fibers using a 0.22 μm filter [19].

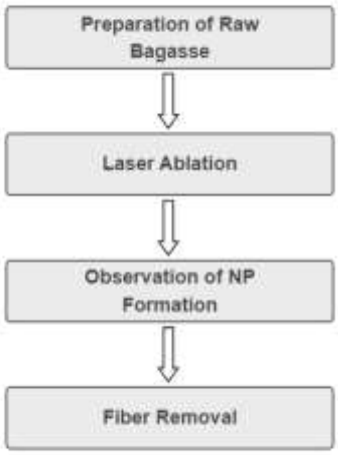

Fig 1. Depicts the process of Laser Ablation Technique.

Sl.no	Source of Si NPs	Property of silica synthesized	Method of synthesis	Conditions	References
1	Rice Husk	Amorphous silica	Pyrolysis	700°C for two hours	[16]
2	Rice Husk	Mesoporous Si NPs	Sol-Gel	Ambient conditions	[17]
3	Sugarbeet bagasse	Ultra-small Si NPs	Laser Ablation	Utilized a commercial nanosecond pulsed Nd:YLF laser	[19]

Table 2- This Table Summarizes Method of Synthesis

4. APPLICATIONS OF SILICON NANOPARTICLES IN DIFFERENT FIELDS SILICON NANOPARTICLES

Si NPs derived from agricultural waste materials find versatile applications in various fields, including biomedicine, energy storage, agriculture, environmental remediation, electronics, and optoelectronics. These applications not only address environmental concerns but also offer innovative solutions across diverse industries.

4.1. Biomedicine

Si NPs exhibit immense potential in the field of biomedicine. They can be employed in drug delivery systems, enabling targeted and controlled drug release, and as imaging agents, enhancing diagnostic capabilities in healthcare. In a study conducted by Ali A. Alshatwi et al., highly pure biogenic silica nanoparticles (bSNPs) were produced from rice husks, a cost-effective agricultural resource. The bSNPs, obtained through an acid digestion process and calcination, exhibited amorphous, spherical morphology with diameters ranging from 10 to 30 nm. They were found to be biocompatible with human lung fibroblast cells (hLFCs) in in vitro tests. These findings suggest that bSNPs hold promise as an alternative to synthetic silica for various applications, including biomedicine and food additives [11].

4.2. Energy Storage

Si NPs have the potential to significantly enhance the performance of lithium-ion batteries, increasing their capacity and cycle life. This hold promises for addressing energy storage challenges. A. Vadivel Murugan and co-workers developed an environmentally friendly method to extract silica from bamboo culm, rice husk, and sugarcane bagasse using microwave-assisted solid-state ashing (MW-SS) and then converted it into crystalline silicon (Si) through microwave-assisted magnesiothermic reduction (MW-MR). This resulted in the creation of porous Si networks. They also combined the Si with various carbon-based materials, leading to improved delithiation capacities in comparison to pristine Si from rice husk. This research showcases the potential of agricultural residues as sustainable sources for nanoporous crystalline Si production, offering a cost-effective and energy-efficient approach for lithium-ion battery anodes [12]. Nian Liu et al. demonstrated the synthesis of pure silicon nanoparticles (Si NPs) from rice husks. These Si NPs possess a small size and porous structure, making them highly effective as anodes in lithium-ion batteries. They exhibit outstanding performance with a remarkable reversible capacity, seven times greater than that of graphite anodes, and maintain 86% capacity retention over 300 charge-discharge cycles. By utilizing rice husks as the raw material source, this research highlights the potential for energy-efficient, environmentally friendly, and large-scale synthesis of cost-effective and functional Si nanomaterials [20].

4.3. Agriculture

Si NPs have shown the ability to enhance crop growth, improve nutrient uptake, and mitigate the effects of abiotic stressors, making them invaluable for sustainable agriculture practices. Nalan Oya San and colleagues developed a single-step laser ablation technique to produce silica nanoparticles from sugarbeet bagasse. This method yielded smaller silica nanoparticles compared to traditional NaOH treatment. The resulting silica nanoparticles showed a positive impact on microalgae growth, demonstrating their potential for various applications [19]. Rajiv Periakaruppan and co-workers achieved green synthesis of silica nanoparticles using Euphorbia thymifolia L. extract. Characterization confirmed the production of spherical, amorphous silica nanoparticles composed of Si and O elements. These nanoparticles were found to enhance Sorghum bicolor seed germination, indicating their potential for use in agriculture [13].

4.4. Environmental Remediation

The adsorption properties of Si NPs can be harnessed for removing contaminants from water and soil, offering solutions for environmental cleanup efforts. Vinoda BM and colleagues developed silicon dioxide nanoparticles (SiO_2 NPs) using rice husk ash (RHA) and employed them for the photocatalytic degradation of methyl red dye in aqueous solutions. The SiO_2 NPs, obtained through an alkaline precipitation method, were amorphous in nature and exhibited efficient photocatalytic activity for dye removal, particularly methyl red [14]. In addressing the challenge of arsenic-contaminated water irrigation in agriculture, Thanaseelan Balasubramanium et al. explored the application of silica nanoparticles (NPs) for arsenic removal. They found that silica NPs efficiently adsorb arsenic, as demonstrated by spectrophotometric analysis. The synthesis of these nanomaterials is cost-effective and straightforward, offering a competitive solution for arsenic removal in comparison to other commercially available adsorbents [21].

4.5. Electronics and Optoelectronics

Si NPs are instrumental in the development of advanced electronic devices, such as transistors and sensors, and in the creation of novel photonic materials, further advancing technology. Sandeep Bose and his team developed an affordable method to produce luminescent silicon nanoparticles (Si NPs) using rice husk as a silicon source and rapid microwave heating. These Si NPs, with an average diameter of approximately 4.9 nm, exhibit stable green luminescence with a high quantum yield of about 60%. They maintain their luminescence over extended periods under UV irradiation, making them superior to other luminescent materials. When combined with red and blue luminescent Si NPs, they create energy-efficient white light, matching pure white light's color coordinates. This white light-emitting material performs comparably to commercial LED bulbs and even outperforms CFLs [22]. A. A. Ebnalwaled and colleagues synthesized mesoporous silica nanoparticles from rice husk ash and used them as nanofillers in polyimide/silica hybrid nanocomposite films. These films exhibited various optoelectronic properties based on silica NP concentration, affecting transparency, UV absorption, dielectric constant, charge carrier concentration, and wettability. This eco-friendly and cost-effective approach offers versatility in tailoring film properties for different applications [15].

Sl.no	Source of Si NPs	Method of synthesis	Application	References
1	Rice husks	Acid digestion followed by calcination	Biomedical	[11]
2	Bamboo culm (BC), rice husk (RH), and sugarcane bagasse (SB)	Microwave-assisted solid-state ashing technique	Energy Storage	[12]
3	Rice husks	Pyrolysis	Energy Storage	[20]
4	Sugarbeet bagasse	Laser ablation	Agriculture	[19]
5	Euphorbia thymifolia L. extract	Sol-gel	Agriculture	[13]
6	Rice husk ash	Alkaline precipitation method	Environmental Remediation	[14]
7	Corn Cob	Sol-gel	Environmental Remediation	[21]
8	Rice husks	Rapid microwave heating	Electronics	[22]
9	Rice husks	pyrolysis	Optoelectronics	[15]

Table 2-This table summarizes the applications of silicon nanoparticles derived from agricultural waste materials in various fields.

5. CONCLUSION

The synthesis of Si NPs from agricultural byproducts offers a sustainable and versatile approach with wide-ranging applications in agriculture, healthcare, environmental remediation, and energy storage. This eco-friendly method aligns with principles of sustainability, reducing waste while providing a cost-effective alternative to traditional Si NP production. Si NPs have shown exceptional promise, particularly in energy storage, where they enhance lithium-ion battery performance, addressing renewable energy storage challenges. In agriculture, they can improve plant health and contribute to sustainable farming practices, addressing food security concerns. Additionally, Si NPs derived from agricultural byproducts hold potential in biomedicine for drug delivery, imaging, and diagnostics, with ongoing research aiming for breakthroughs in targeted therapy and non-invasive medical procedures. To fully unlock the potential of Si NPs from agricultural waste, further research and development are essential. This field contributes to a greener and more sustainable future, providing innovative solutions to pressing challenges across various industries.

In summary, while significant progress has been made in synthesizing Si NPs from agricultural waste, challenges like achieving uniformity, scalability, and safety assessments remain. Nevertheless, this field holds immense promise in terms of sustainability and cost-effectiveness, offering diverse applications. Continued research is likely to address pressing challenges in energy, agriculture, and healthcare, ultimately contributing to a more sustainable and prosperous future by harnessing agricultural waste materials.

6. RESEARCH GAP

The synthesis of Si NPs from agricultural byproducts offers sustainability in nanomaterial production. However, critical research gaps must be addressed to drive progress. Tackling these gaps is vital for advancing synthesis and promoting eco-friendly nanomaterials. Thorough exploration and discussion of these gaps are necessary to unlock the field's full potential.

- Lack of Comprehensive Synthesis Methods- A critical research gap is the absence of a standardized method for synthesizing Si NPs from agricultural waste. Current research lacks systematic comparisons of materials like rice husks, wheat straw, and sugarcane bagasse in terms of efficiency, purity, and scalability. Establishing a standardized protocol considering different agricultural byproducts is needed.
- Limited Understanding of Reaction Mechanisms- A significant research gap exists in the limited understanding of the chemical and physical mechanisms behind Si NP synthesis from agricultural byproducts. Deeper investigations into kinetics, thermodynamics, and intermediate species are needed to enhance the efficiency and control of the synthesis processes.
- Diverse Applications and Performance Evaluation- There's a need for further studies assessing the real-world performance of Si NPs in specific applications like drug delivery, sensors, batteries, and photovoltaics. Existing research often focuses on synthesis but lacks comprehensive evaluations of Si NPs' suitability and effectiveness in practical use cases.
- Environmental and Economic Assessment- Further studies are needed to assess Si NPs performance in real-world applications like drug delivery, sensors, batteries, and photovoltaics, as current research primarily focuses on synthesis without comprehensive practical evaluations.

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