

From Agricultural Biowaste to Sustainable Nanofertilizers: A Circular Approach for Nanosilica Production, Nutrient Management and Environmental Conservation

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Abstract—The increasing generation of agricultural residues, declining soil fertility, inefficient fertilizer use, and environmental degradation have created a need for integrated approaches that simultaneously address waste management and sustainable crop production. Agricultural biowastes such as rice husk, maize husk, wheat straw, sugarcane bagasse and other silica-rich residues represent renewable resources for the production of value-added nanomaterials. Among these materials, nanosilica (SiO₂ nanoparticles) has attracted increasing attention because of its high surface area, tunable physicochemical properties, potential plant availability and ability to influence plant growth, nutrient acquisition and tolerance to environmental stresses. Rice husk is particularly important because it contains a substantial proportion of silica and can be transformed into relatively high-purity amorphous silica through thermal, chemical, hydrothermal or combined extraction approaches. Recent literature indicates that pretreatment, calcination temperature, extraction chemistry and particle formation strongly influence silica purity, morphology, surface characteristics and agricultural performance. This review examines the complete conceptual pathway from agricultural biowaste generation to nanosilica-based nanofertilizer development. Particular attention is given to the composition of silica-rich agricultural residues, pretreatment and extraction strategies, formation and characterization of nanosilica, and the role of nanosilica in plant nutrition. The mechanisms through which silicon can improve nutrient acquisition, photosynthesis, antioxidant defense, water relations and tolerance to drought, salinity, heavy-metal toxicity and biotic stresses are discussed. The review further evaluates the potential of nanosilica to improve nutrient-use efficiency and reduce dependence on conventional fertilizer inputs. A comparative perspective on rice husk and maize-derived

biomass is included because feedstock composition and silica recovery can substantially influence the final nanomaterial. The environmental significance of converting agricultural residues into functional nanofertilizers is discussed within the framework of circular economy and sustainable agriculture. Finally, challenges related to reproducibility, dose optimization, nanoparticle fate, soil–plant interactions, ecotoxicity, life-cycle assessment, economic feasibility and field-scale validation are identified. The integration of agricultural-waste valorization with nanosilicon-based nutrient management offers a promising pathway toward circular, resource-efficient and environmentally responsible agricultural systems.

Index Terms—Nanosilica, Nano fertilizer, nutrient-use efficiency, sustainable agriculture, circular economy, environmental conservation.

I. INTRODUCTION

Agriculture generates large quantities of crop residues every year. Rice husk, wheat straw, maize residues, sugarcane bagasse, rice straw and other lignocellulosic materials are frequently treated as low-value wastes despite containing carbon, minerals and other useful components. Inappropriate disposal or uncontrolled combustion of these residues can contribute to particulate emissions, greenhouse-gas release and local environmental pollution. At the same time, intensive agricultural production increasingly depends on synthetic fertilizers, whose inefficient application can result in nutrient losses through leaching, volatilization and runoff. [13, 17, 19, 58, 59, 76] The simultaneous occurrence of agricultural-waste

accumulation and inefficient nutrient management creates an opportunity for circular resource utilization. Rather than considering crop residues solely as wastes, they can be regarded as secondary raw materials for producing value-added products. Among cereal residues, rice husk is particularly interesting because of its naturally high silica content. Several reviews have identified rice husk as an important renewable precursor for silica and nanosilica production. [28, 30, 34, 39, 51, 58, 59, 84]

Silicon (Si) occupies a distinctive position in plant nutrition. Although it is generally not classified as an essential element for higher plants, numerous studies have demonstrated beneficial effects of Si on plant growth, structural development, disease resistance and tolerance to abiotic stresses. Plants generally absorb Si from soil solution as monosilicic acid, H_4SiO_4 , after which it can be transported and deposited in plant tissues.

The potential agricultural significance of Si is especially relevant under environmental stress. Silicon supplementation has been associated with improved tolerance to drought, salinity, metal toxicity, temperature stress and pathogen attack. Reviews of silicon physiology indicate that its effects can involve physical deposition, regulation of antioxidant systems, modification of nutrient balance and stimulation of plant defense mechanisms.

Conventional silicon fertilizers, however, may suffer from limitations associated with solubility, availability and inefficient delivery. Nanosilica offers an alternative because reducing particle dimensions increases specific surface area and can alter interactions with water, soil minerals and plant tissues. The development of nanosilica from agricultural biowaste adds a further sustainability dimension. In this model, crop residues become raw materials for nanomaterial production, and the resulting material can potentially return to agriculture as a nutrient or biostimulant. This creates a circular pathway. [28, 32, 34, 39]

Agricultural crop → agricultural residue → silica recovery → nanosilica production → nano fertilizer → crop nutrition and stress management → improved resource utilization.

The objective of this review is therefore to critically discuss this complete pathway, with particular emphasis on silica-rich agricultural residues, especially rice and maize-derived biomass, nanosilica synthesis and characterization, plant nutrition, environmental benefits, limitations and future research requirements.

II. AGRICULTURAL BIOWASTE AS A RENEWABLE RESOURCE FOR NANOMATERIAL PRODUCTION

Agricultural residues contain organic fractions such as cellulose, hemicellulose and lignin together with inorganic minerals. The inorganic fraction can include silica, potassium, calcium, magnesium, phosphorus and other mineral constituents.

The concentration and chemical form of these constituents vary considerably with crop species, cultivar, soil conditions and agricultural practices. [28, 30, 32, 39] Cereal residues are particularly relevant to silica recovery. Rice plants are recognized as silicon accumulators, and rice husk can contain a considerable amount of silica concentrated in the ash after controlled thermal treatment. Consequently, rice husk has been widely investigated as a precursor for amorphous silica, mesoporous silica and silica nanoparticles. [1, 7, 10, 28, 32]

Maize-derived residues can also contain silica, although their mineral composition and silica concentration differ from rice husk. Therefore, the quality and yield of silica obtained from different residues should not be assumed to be identical. Comparative assessment of feedstock composition is important when developing a reproducible agricultural nano fertilizer. [28, 32, 77, 83]

Agricultural-waste valorization has two major environmental advantages. First, it reduces the amount of residue requiring disposal. Second, it replaces part of the requirement for conventional mineral raw materials. The conversion of agricultural residues into functional materials therefore fits the broader principles of circular economy.

Table 1. Major Agricultural Biowastes as Potential Silica Sources

Agricultural biowaste	Major significance	Silica potential	Major processing considerations	Potential application
Rice husk	One of the most extensively studied silica-rich residues	High	Washing, acid pretreatment, controlled calcination, alkaline extraction	Nanosilica, nano fertilizer, adsorbent
Rice husk	Abundant cereal residue	Moderate	Ashing and purification required	Silica and silicon-based materials
Maize husk/residue	Widely available agricultural residue	high Variable	Pretreatment and extraction optimization required	Nanosilica and agricultural nanomaterials
Wheat straw	Large-volume cereal residue	Moderate	Controlled thermal treatment and purification	Silica-based materials
Sugarcane bagasse	Major agro-industrial residue	Variable	Ash generation and silica recovery	Silica, composites, nanomaterials
Other crop residues	Regionally available biomass	Crop-dependent	Feedstock-specific optimization	Value-added nanomaterials

III. RICE HUSK AS A STRATEGIC SOURCE OF SILICA

Rice husk represents one of the most extensively studied agricultural residues for silica production. Its importance originates from its relatively high silica concentration and the possibility of recovering silica following controlled combustion or chemical extraction. The basic conversion pathway can be represented as:

Rice husk → pretreatment → controlled thermal treatment → rice husk ash → silica extraction → purification → nanosilica formation.

The first step generally involves washing and drying to remove soil particles and soluble impurities. Acid pretreatment may subsequently be used to remove metallic impurities such as potassium, calcium, magnesium and iron. Controlled thermal treatment converts the organic fraction into gases and carbonaceous residues while concentrating silica in the resulting ash. Temperature is a particularly important parameter. Excessive temperature or prolonged heating can promote transformation of amorphous silica into more crystalline phases, whereas controlled conditions can favor retention of amorphous silica. The extraction strategy also affects purity, morphology and surface characteristics.

Table 2. Methods for Nanosilica production from agricultural biowaste

Synthesis approach	Basic principle	Advantages	Limitations	Sustainability consideration
Thermal treatment Simple and scalable Requires energy optimization	Biomass is calcined to remove organic matter and concentrate silica	Simple and scalable	High temperature/energy requirement; excessive temperature may cause crystallization	Requires energy optimization
Acid pretreatment + calcination	Acid removes metallic impurities before thermal treatment	Higher silica purity	Acid consumption and wastewater generation	Acid recovery desirable
Alkaline extraction–precipitation	Silica is dissolved as silicate and subsequently precipitated	High-purity silica can be obtained	Requires alkali and acid	Reagent recycling is important

Sol-gel approach	Silicate precursor is converted into silica through hydrolysis/condensation	Good control over particle characteristics	Chemical processing requirements and	Requires reduction of solvent/reagent use
Hydrothermal synthesis	Biomass/silica precursor is processed under controlled temperature and pressure	Potentially improved morphology and lower-temperature processing	Specialized equipment	Potential for greener processing
Biological/green routes	Biological or low-toxicity agents assist material formation	Reduced hazardous chemical use	Still under development	High potential for sustainable synthesis

Thus, an ideal process should not be evaluated solely on silica yield. A genuinely green extraction process should simultaneously consider: silica recovery; purity; particle size; energy consumption; water requirement; chemical consumption; wastewater generation; scalability; economic feasibility; and environmental impact. [28, 32, 77, 49, 50, 84]

IV. MAIZE AND OTHER AGRICULTURAL RESIDUES AS ALTERNATIVE SILICA PRECURSORS

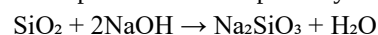
Although rice husk is one of the most established sources of biogenic silica, dependence on a single residue may limit geographical applicability. Maize husk, wheat straw, sugarcane residues and other crop wastes can provide alternative feedstocks. The use of alternative agricultural residues is scientifically important because their mineral composition differs from rice husk. Such differences may influence silica recovery, silica purity, particle morphology, surface chemistry, crystallinity, particle-size distribution and fertilizer performance. Therefore, comparative studies between agricultural residues can provide valuable information regarding feedstock suitability. A comparative approach involving rice- and maize-derived silica is particularly relevant for regions where both crops are extensively cultivated.

V. GREEN ROUTES FOR NANOSILICA PRODUCTION

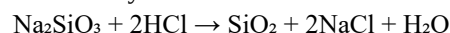
Nanosilica can be prepared using physical, chemical, sol-gel, precipitation, hydrothermal and other approaches. For agricultural-waste-derived silica, a common pathway involves conversion of biomass to

silica-rich ash followed by alkaline dissolution and precipitation.

A simplified chemical pathway is:



followed by acidification:



The precipitated silica can subsequently be washed, dried and processed into nanoscale particles [78, 83]. However, conventional acid-base extraction can generate chemical waste. Consequently, recent research has focused on hydrothermal processing, biological approaches, lower-energy routes and improved reagent recovery.

A green synthesis strategy should therefore aim for: high silica recovery + high purity + controlled particle size + low chemical consumption + low energy requirement + minimal secondary waste.

VI. CHARACTERIZATION OF WASTE-DERIVED NANOSILICA

Proper characterization is essential because the term “nanosilica” should not be assigned solely on the basis of a synthesis procedure. Multiple complementary analytical techniques are required.

1) Fourier Transform Infrared Spectroscopy [FTIR]: FTIR can identify characteristic Si–O–Si and Si–OH vibrations. The presence of broad hydroxyl-related signals can provide information about surface silanol groups. [22, 28, 77, 82].

2) X-ray Diffraction [XRD]: XRD is useful for determining the structural state of silica. Broad halos generally indicate an amorphous

structure, whereas sharp diffraction peaks indicate crystalline phases.

3) Scanning Electron Microscopy [SEM]:

SEM provides information about particle morphology, aggregation and surface structure.

4) Transmission Electron Microscopy [TEM]:

TEM can provide more direct information about nanoscale particle morphology and approximate particle dimensions.

5) Particle-Size Analysis:

Particle-size distribution is important because aggregation can cause the hydrodynamic size of particles in suspension to differ substantially from their primary particle size.

6) Surface Area and Porosity:

Brunauer-Emmett-Teller [BET] surface-area analysis can provide information about the accessible surface of the material. Higher surface area can influence adsorption, dispersion and interactions with nutrients and biological surfaces.

Table 3. Characterization Techniques for Agricultural-Biowaste-Derived Nanosilica

Technique	Major information obtained	Importance in nanosilica research
FTIR	Si-O-Si, Si-OH and other surface functional groups	Confirms silica-related bonding and surface chemistry
XRD	Amorphous/crystalline nature	Determines structural state of silica
SEM	Surface morphology and particle aggregation	Evaluates particle morphology
TEM	Primary particle morphology and nanoscale dimensions	Provides direct nanoscale structural information
DLS/ particle-size analysis	Particle-size distribution in suspension	Important for dispersion and aggregation
BET	Specific surface area and pore characteristics	Important for adsorption and surface interactions
EDS/EDX	Elemental composition	Helps assess silica purity and inorganic impurities

VII. SILICON AND PLANT NUTRITION

Silicon is absorbed mainly in the form of monosilicic acid. In rice and other Si-accumulating plants, specific transport systems facilitate silicon uptake and distribution. Silicon can subsequently accumulate in shoots and tissues where it contributes to structural and physiological responses. The beneficial effects of Si are particularly evident under stress conditions. Silicon can influence nutrient balance, water relations, photosynthetic performance, antioxidant defense and structural properties. [11, 14, 20, 21, 52, 65, 63, 65] An important feature of Si nutrition is that the response is species-dependent. Plants differ substantially in their ability to absorb, transport and accumulate Si. Consequently, the optimum dose of nanosilica cannot be generalized across all crops. [4, 11, 13]

VIII. NANOSILICA AS A NANOFERTILIZER

Nanofertilizers are designed to improve nutrient delivery, nutrient availability or fertilizer-use efficiency through nanoscale materials. Their proposed advantages include improved interaction with plant surfaces, controlled nutrient release, greater surface area and enhanced delivery efficiency. [34, 52, 42, 51, 58, 59]

Nanosilica can be considered a silicon-based nanofertilizer or nano-enabled plant-growth-promoting material. Its potential agricultural functions include supplying plant-available silicon; improving nutrient uptake; supporting photosynthesis; improving root development; enhancing antioxidant defense; improving water-use efficiency; mitigating drought stress; reducing some forms of metal toxicity; strengthening plant structural tissues; and improving resistance against selected pathogens. [22, 27, 34, 39, 51, 52, 58, 59]

IX. INFLUENCE OF NANOSILICA ON NUTRIENT-USE EFFICIENCY

One of the most important concepts in sustainable fertilizer management is nutrient-use efficiency (NUE). Conventional fertilizers can undergo substantial losses through leaching, volatilization, fixation and runoff. Nanosilica may indirectly influence nutrient-use efficiency by modifying root development, nutrient transport and plant

physiological responses. Silicon has been reported to interact with the uptake and distribution of several nutrients, including nitrogen, phosphorus, potassium, iron, zinc and other micronutrients. [4,11, 14, 34, 39, 85, 93, 97, 98]

Under nutrient stress, nanosilica may help plants maintain physiological activity by improving antioxidant protection and modifying nutrient-related processes. However, the relationship is not universally positive. Responses depend on particle concentration, particle characteristics, crop species, soil properties, application method and environmental conditions. [4,11, 14, 34, 39, 85, 93, 97, 98].

Useful indicators include:

Agronomic efficiency (AE) = (Yield treated – Yield control) / Nutrient applied

Apparent nutrient recovery efficiency (RE) = (Nutrient uptake treated – Nutrient uptake control) / Nutrient applied

X. NANOSILICA AND DROUGHT STRESS

Drought is one of the major limitations to agricultural productivity. Water deficiency reduces cell expansion, photosynthesis, stomatal conductance and nutrient uptake while increasing oxidative stress [11, 14, 20, 22, 23]. Silicon supplementation has been associated with improved plant water status, antioxidant activity and photosynthetic performance. Nanosilica may provide an efficient form of silicon because of its high surface area and physicochemical properties.

The possible mechanism can be summarized as:
Nanosilica application → improved Si availability → improved water relations + enhanced antioxidant defense + improved photosynthesis → reduced oxidative damage → improved growth under drought.

XI. NANOSILICA AND SALINITY STRESS

Salinity can cause both osmotic stress and ionic toxicity. Excess Na⁺ accumulation interferes with potassium uptake and disrupts cellular metabolism. Silicon has been investigated as a means of reducing salt-induced physiological damage. Proposed mechanisms include regulation of ion balance, improved antioxidant defense, stabilization of membranes and reduction of oxidative damage.

Nanosilica may therefore represent a potential Si delivery system under saline conditions. Nevertheless, the effectiveness of treatment depends on concentration and application route. [20, 26, 52, 55, 57, 62]

XII. NANOSILICA AND HEAVY-METAL STRESS

Heavy metals such as cadmium, lead, chromium and arsenic can enter agricultural soils through industrial emissions, wastewater, mining and contaminated amendments. Silicon can reduce metal toxicity through several mechanisms, including immobilization in soil, modification of root uptake, complexation and sequestration within plant tissues. Nanosilica may strengthen these effects because its high surface area can facilitate interactions with dissolved ions and soil constituents.

XIII. NANOSILICA AND SALINITY STRESS

Silicon has long been associated with increased resistance against several plant diseases. Silicon deposition in plant tissues can provide a physical barrier, while Si-associated biochemical responses may stimulate plant defense pathways. [14, 20, 55, 56, 63, 65, 90].

Nanosilica may therefore provide a dual function: nutrient/biostimulant function + plant-defense-supporting function. This could contribute to integrated crop management by potentially reducing dependence on chemical pesticides in certain systems.

XIV. POSSIBLE MECHANISMS OF NANOSILICA-MEDIATED PLANT RESPONSES

The major mechanisms proposed in the literature can be grouped into five categories. [14, 20, 55, 56, 63, 65, 85, 93]

- 1) Physical Mechanism- Silicon can polymerize and accumulate in plant tissues, contributing to mechanical strength.
- 2) Nutritional Mechanism- Nanosilica can act as a silicon source and may influence uptake or utilization of other nutrients.
- 3) Antioxidant Mechanism- Si treatment can stimulate enzymatic and non-enzymatic antioxidant systems, helping plants control reactive oxygen species.
- 4) Molecular Mechanism- Silicon can influence signaling pathways associated with stress responses,

although the precise molecular mechanisms remain incompletely resolved.

- 5) Soil–plant interaction mechanism–Nanosilica can interact with soil particles, organic matter, nutrients and metal ions, potentially changing their availability to roots.

XV. COMPARATIVE PERSPECTIVE: RICE HUSK VERSUS MAIZE-DERIVED SILICA

Rice-husk-derived nanosilica has already been evaluated in crops including maize. Recent research reported improved growth and micronutrient responses in hybrid maize at selected nanosilica doses but also observed reductions at higher concentrations, emphasizing the importance of dose optimization. ^[14, 20, 55, 56, 63, 65, 89, 90]

Table 4. Potential effects of nanosilica on plant

Plant response	Possible effect of nanosilica	Proposed mechanism
Germination	Improved germination under selected conditions	Improved water relations and metabolic activity
Root development	Increased root growth in appropriate concentrations	Improved nutrient acquisition and physiological activity
Shoot growth	Increased biomass under suitable conditions	Improved photosynthesis and nutrient status
Photosynthesis	Maintenance /Improvement under stress	Improved chlorophyll stability and reduced oxidative damage
Nutrient uptake	Improved acquisition/ utilization of selected nutrients	Silicon-mediated changes in root and nutrient phycology

XVI. CIRCULAR ECONOMY PERSPECTIVE

The proposed agricultural biowaste-to-nanofertilizer pathway can be represented as:

Crop production → Agricultural residue generation → Residue collection and pretreatment → Silica recovery → Nanosilica synthesis → Physicochemical characterization → Nanofertilizer application →

Improved nutrient management and stress tolerance → Crop production.

This represents a circular material pathway rather than a linear waste-disposal model. The environmental advantages potentially include reduction of agricultural residue accumulation; reduction in open burning; recovery of valuable mineral components; production of value-added nanomaterials; improved nutrient-use efficiency; possible reduction in excessive fertilizer application; improved agricultural resilience; and opportunities for decentralized biomass utilization. ^[30, 34, 39, 41, 47, 51, 58, 59, 66, 84]

XVII. ENVIRONMENTAL SUSTAINABILITY AND LIFE-CYCLE CONSIDERATIONS

The phrase “green synthesis” should be used carefully. A process is not automatically environmentally sustainable merely because the precursor is agricultural waste. A rice-husk-derived nanosilica process involving large quantities of acid, alkali, water and energy may generate significant environmental burdens. Therefore, sustainability assessment should consider biomass collection, transportation, washing, drying, calcination, chemical extraction, wastewater treatment, nanoparticle drying, packaging, transport to farms and final environmental fate. A life-cycle assessment should ideally compare the waste-derived nanosilica route with conventional silicon fertilizers or commercially produced nanosilica.

XVIII. ENVIRONMENTAL RISKS AND NANOTOXICOLOGICAL CONSIDERATIONS

The potential benefits of nanofertilizers must be considered together with their environmental risks. Nanoparticles may interact with soil microorganisms, earthworms, beneficial fungi, plant roots, aquatic systems, soil organic matter and food-chain organisms.

The effects may depend strongly on concentration, particle size, surface chemistry, aggregation and environmental conditions. Nanosilica should not automatically be classified as safe merely because silica is abundant in nature. Nanoscale materials can exhibit different physicochemical behavior from bulk materials.

Long-term experiments are therefore needed to determine nanoparticle persistence, transformation,

aggregation, dissolution, soil accumulation, microbial effects, plant translocation and possible food-chain transfer.

XIX. KNOWLEDGE GAPS

- 1) Lack of standardized Synthesis-Different researchers use different calcination temperatures, extraction chemicals and precipitation conditions, making direct comparison difficult.
- 2) Feedstock Variability-Agricultural residues differ according to cultivar, geographical location, soil and processing conditions.
- 3) Limited field-scale validation-A large proportion of nanosilica research remains laboratory- or pot-based.
- 4) Dose-response uncertainty-The same nanosilica concentration may have beneficial effects in one crop and inhibitory effects in another.
- 5) Limited long-term Studies-Long-term soil accumulation and ecological consequences remain insufficiently characterized.
- 6) Incomplete sustainability assessment-Few studies simultaneously evaluate silica yield, energy consumption, chemical use, economic cost and environmental impact.
- 7) Limited comparative Studies-Direct comparison between nanosilica derived from different agricultural residues remains relatively underdeveloped.
- 8) Insufficient integration of nano fertilizer and circular-economy concepts-Many studies examine either agricultural-waste valorization or nanofertilizer performance, but fewer integrate both aspects into one complete sustainability framework.

XX. PROPOSED RESEARCH FRAMEWORK

Stage I: Feedstock selection- Rice husk, maize husk, wheat residue and other silica-containing agricultural residues are selected.

Stage II: Pretreatment- Washing, drying and impurity removal is performed.

Stage III: Silica Recovery-Thermal and/or chemical extraction is optimized.

Stage IV: Nano silica Synthesis-Purified silica is converted into nanoscale material.

Stage V: Characterization- FTIR + XRD + SEM/TEM + particle-size analysis + surface-area analysis.

Stage VI: Nano fertilizer formulation-Nano silica may be evaluated independently or incorporated into a nutrient formulation.

Stage VII: Plant experiment- Parameters should include germination, root length, shoot length, biomass, chlorophyll, photosynthesis, relative water content, antioxidant enzymes, nutrient uptake, Si accumulation and yield components.

Stage VIII: Environmental Evaluation-Soil properties, nutrient availability, microbial responses and possible nanoparticle accumulation should be evaluated.

Stage IX: Sustainability Assessment-Techno-economic analysis and life-cycle assessment should be incorporated before recommending field-scale implementation.

XXI. FUTURE PERSPECTIVES

The next stage of research should move from demonstrating that waste-derived nanosilica can be produced toward determining whether it can be produced reproducibly, economically and sustainably at agricultural scale. Future investigations should prioritize low-energy silica extraction; reduced chemical consumption; recovery and recycling of extraction reagents; standardized particle-size control; comparative studies of rice, maize and other residues; crop-specific dose optimization; integration with N, P and K fertilizers; controlled-release formulations; field-scale trials; soil microbiome studies; long-term environmental fate; life-cycle assessment; techno-economic assessment; and regulatory frameworks for agricultural nanomaterials. [28, 32, 34, 42, 49, 50, 51, 58, 59, 66, 84]

The development of multifunctional nano fertilizers combining nanosilica with essential nutrients could be particularly important.

XXII. CONCLUSION

Agricultural biowaste should no longer be considered solely as a disposal problem. Silica-rich residues provide an opportunity to convert an underutilized biomass resource into a value-added nanomaterial with potential agricultural applications. Among available residues, rice husk has emerged as a particularly important precursor for silica and nanosilica because of its silica content and widespread availability. Maize and other crop residues provide additional opportunities for developing region-

specific and comparative biomass-to-nanomaterial pathways. Nanosilica represents a promising component of sustainable nanofertilizer systems because silicon can influence plant nutrition, antioxidant defense, structural development and tolerance to environmental stresses. The combination of agricultural-waste valorization and nanosilica-based nutrient management therefore offers a conceptual bridge between waste management, nanotechnology, plant nutrition and environmental conservation. [11, 14, 22, 27, 34, 39, 51, 52, 55, 56, 85, 93, 97, 98, 100]

However, the sustainability of such systems cannot be established solely from laboratory demonstrations. Feedstock variability, chemical consumption, energy requirements, nanoparticle aggregation, dose-dependent phytotoxicity, soil interactions and long-term ecological effects must be systematically evaluated. The most promising research direction is consequently not simply the production of nanosilica from agricultural waste, but the development of an integrated and measurable circular nanofertilizer platform in which waste conversion, nanosilica quality, plant response, nutrient-use efficiency, environmental safety and life-cycle sustainability are evaluated together.

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