

Efficacy of Foliar and Soil Nano-Silica Application on Rice (*Oryza sativa* L.) Growth and Yield: A Literature Review

Chelya Syarifatul Balqis¹, Oviyanti Mulyani², Emma Trinurani Sofyan³,
Nadia Nuraniya Kamaluddin⁴, Farida Damayanti⁵

¹Padjadjaran University, Faculty of Agriculture,
Ir. Soekarno Road KM.21, Jatinangor, Sumedang, Indonesia

Abstract: Rice (*Oryza sativa* L.) is a silicon-accumulating crop that requires adequate silicon (Si) supply to support growth, yield, and tolerance to biotic and abiotic stresses. Conventional silicon fertilizers exhibited low uptake efficiency, leading to the development of nano-silica fertilizers as an alternative, since their small particle size and large surface area were believed to enhance nutrient uptake efficiency. Nano-silica was commonly applied through two pathways, namely foliar spray and soil application, yet evidence on the relative advantage of each method in rice remained scattered across diverse cultivation conditions and had not been systematically synthesized. This review aimed to synthesize and compare the agronomic efficacy of foliar and soil applications of nano-silica in rice, and to identify factors influencing the superiority of each method. A literature search was conducted across international scientific databases using keywords related to nano-silica, foliar application, soil application, and rice, focusing on publications from the past five years. The results show that foliar application generally provides faster nutrient uptake and greater dose efficiency, whereas soil application tends to be more effective under specific soil conditions such as calcareous, heavy metal-contaminated, or highly saline soils. Effective doses vary widely depending on application method, rice variety, and growth stage, while combined foliar and soil application shows potential for more optimal outcomes than single applications. This review concludes that nano-silica application method in rice should be tailored to field conditions and agronomic goals, and recommends dose standardization and large-scale field trials for future research.

Keywords: foliar application, nanofertilizer, nano-silica, rice (*Oryza sativa*), soil application

1. Introduction

Rice (*Oryza sativa* L.) is a staple food crop that supports the caloric needs of a large proportion of the world's population, making productivity improvement a continuing priority for national and global food security. Although silicon (Si) is not classified as an essential nutrient, its presence is highly beneficial for rice, which is known as a high-Si-accumulating crop — sufficient Si uptake contributes to stem strength and lodging resistance [1], as well as tolerance to various biotic and abiotic stresses [2]. However, long-term intensive rice cultivation depletes the available Si reserves in the soil, making Si supplementation through fertilization an agronomic necessity, particularly in sub-optimal land [3].

Conventional silicon fertilizers — whether in the form of calcium silicate, potassium silicate, or silicic acid — generally have low absorption efficiency and require large application doses, which burdens farmers' production costs. The development of nanotechnology has opened new opportunities through nano-silica fertilizer (SiO₂ nanoparticles/SiNPs), which, due to their very small size and large surface area, are claimed to improve nutrient uptake efficiency compared to conventional forms [2], [4]. Nano-silica can also be synthesized from agricultural waste such as rice husk through a relatively simple and low-cost sol-gel method, making it an alternative fertilizer aligned with circular economy principles while also solving the problem of rice milling industry waste utilization [5].

In practice, nano-silica is applied through two main pathways: foliar spray and soil application. Several studies report that foliar application is superior in nutrient uptake speed and dose efficiency due to minimal loss from soil leaching [6]. On the other hand, several studies on other crops show the opposite pattern — for example, in maize, soil amendment with nanoparticles was reported to be more effective than foliar application [7]. In rice itself, the available evidence is scattered across various different growing conditions, with a wide range of effective doses also depending on the application method and the agronomic objective being measured.

Several international literature reviews have discussed the general role of nano-silica in agriculture, including uptake mechanisms, synthesis, and its role in mitigating biotic and abiotic stress across various commodities [2], [8], [4]. However, to the authors' knowledge, there has not been much review that specifically synthesizes and systematically compares the agronomic efficacy of foliar and soil nano-silica application specifically in rice, even though selecting the appropriate application method greatly determines cost efficiency and cultivation success at the farmer level. This gap is the basis and novelty of this literature review.

Therefore, this literature review aims to synthesize scientific evidence regarding the efficacy of nano-silica as a fertilizer in rice through foliar application, soil application, or a combination of both, and to identify the factors (dose, stress condition, and growth stage) that influence which application method is more effective under certain conditions.

2. Methodology

This article was compiled using a literature review method to examine the efficacy of foliar and soil nano-silica application on the growth and yield of rice (*Oryza sativa* L.). Literature sources in this article were obtained through searches on various reputable scientific digital databases, namely Scopus, ScienceDirect, PubMed/PMC, SpringerLink, and Google Scholar. The literature used in this study consists of research articles and review articles published between 2014–2026, with an emphasis on publications from the last five years. The literature was searched using the keywords "nano-silica", "silicon nanoparticle", "SiO₂ nanoparticle", "rice", "*Oryza sativa*", "foliar application", and "soil application".

The writing of this review article refers to the literature review stages proposed by Snyder [9], beginning with topic determination and focus formulation, searching and evaluating appropriate literature sources, and synthesizing the results of published research. The literature obtained was reviewed descriptively and grouped into several topics: the characteristics and synthesis methods of nano-silica, foliar application efficacy, soil/soaking application efficacy, direct comparison between the two application methods, the role of nano-silica in plant stress tolerance (abiotic and biotic), and dose and safety factors of its application in rice. The results were then compared and synthesized to identify the efficacy patterns of each application method, the consistency of the underlying physiological mechanisms, and research gaps that still require further study, particularly regarding drought stress and variations in nanoparticle design.

3. Results and Discussion

3.1 Characteristics of Nano-Silica Used in Rice Studies

Before discussing its agronomic efficacy, it is important to first understand the physical characteristics of the nano-silica used in various rice studies, because the synthesis method and resulting particle size directly affect the reactive surface area, nutrient release rate, and ultimately the uptake efficiency by plant tissue. The nano-silica applied to rice in the reviewed literature originates from two main synthesis pathways: chemical synthesis using pure silica precursors and green synthesis utilizing agricultural waste as an alternative silica source. The green synthesis approach is increasingly developed as it aligns with sustainable agriculture principles and agro-industrial waste utilization, particularly rice husk and rice straw, which are abundantly available in rice-producing countries. A summary of nano-silica characteristics by synthesis category is presented in Table 1.

Table 1: Summary of Studies on Nano-Silica Synthesis Characteristics in Rice

Synthesis Category	Reference	Key Findings
Chemical (commercial)	Ghourai et al. [10]	Pure silica, particle size 15–30 nm
	Ashraf et al. [11]	Pure silica, 99.9% purity, nanoscale
Green synthesis (rice husk/straw)	Larkunthod et al. [12]	Sol-gel from rice husk, 60–135 nm
	Patil et al. [13]	Green synthesis, rice husk, ± 93.14 nm
	Elshayb et al. [14]	HCl + calcination, rice husk, ≈ 43 nm (DLS)
	Ijaz et al. [16]	Green synthesis, rice straw, 10.06–24.37 nm
Green synthesis (other sources)	Tourky et al. [15]	Chia seed extract; Bio-SiNPs more stable & higher surface area than Chem-SiNPs

Data in Table 1 show that rice husk and straw are the dominant raw materials for green synthesis, consistent with their abundant availability as agricultural waste in rice-producing countries such as Indonesia, Thailand, and Egypt, where most of these studies were conducted. The difference in particle size between synthesis methods — for example 60–135 nm in Larkunthod et al. [12] compared to ± 93 nm in Patil et al. [13], despite both using rice husk — indicates that process conditions such as calcination temperature, acid concentration, and precipitation method also influence the final particle characteristics, not merely the raw material type. Compared to bulk silica or conventional silicate, nano-silica is consistently reported to have advantages in surface area and reactivity [17], which theoretically allows more intensive interaction with cell

membranes and plant nutrient transport pathways. However, this high surface area also means excessive reactivity has the potential to cause adverse effects at certain concentrations, a pattern discussed further in section 3.6. This difference in characteristics partly explains why the effective doses reported in the following sections vary widely between studies, since nano-silica of different sizes and sources cannot be treated as a single uniform material.

3.2 Foliar Application Efficacy of Nano-Silica in Rice

Foliar application, namely spraying nano-silica solution directly onto the leaf surface, is the most widely tested method in the reviewed literature. Its popularity stems from ease of field application and the general assumption that uptake through stomata and leaf cuticles occurs faster than the root pathway. Six studies in this review tested foliar application for various agronomic purposes, ranging from growth and yield improvement under normal conditions, salinity stress mitigation, to the effect of application timing on effectiveness, with effective doses varying widely depending on the purpose and cultivation conditions tested. A summary of findings by application purpose category is presented in Table 2.

Table 2: Summary of Studies on Foliar Nano-Silica Application Efficacy in Rice

Purpose Category	Reference	Key Findings
General growth & yield	Gopal et al. [18]	200 ppm optimum; grain yield +28.60%, straw yield +19.16% vs silicic acid
	Elshayb et al. [14]	30–90 ppm; growth & yield increased under 3 irrigation regimes
	Slameto et al. [3]	4 mL/L (Nano-S-Si); height, tillering, leaf number increased on sub-optimal soil
Salinity tolerance	Alam et al. [19]	200 mM; morpho-physiological parameters significantly improved
	Larkunthod et al. [12]	120 mg/L; photosynthesis (PN) +18 to +116%, H ₂ O ₂ -8 to -31%
Growth stage effect	Sheykhzadeh et al. [20]	Effectiveness varies depending on growth stage of application

The six studies in Table 2 consistently report positive benefits of foliar application on growth, physiological, and yield parameters, both under normal conditions and salinity stress, confirming that the foliar pathway is effective as a means of Si supplementation in rice. This is consistent with the argument that foliar application excels in response speed due to direct uptake through stomata and cuticles, minimizing losses from soil fixation or irrigation leaching, as reviewed generally by Ding et al. [6] regarding the advantages of foliar nanofertilizers over conventional methods. However, the reported effective dose range is very wide, from 4 mL/L liquid formulation to 200 mM SiO-NPs solution depending on formulation and measurement purpose, indicating no single dose standard can be universally recommended for foliar application in rice. This variation is likely related to differences in nano-silica characteristics as discussed in Table 1, besides differences in rice variety and testing conditions. Sheykhzadeh et al. [20] add that foliar effectiveness is also not static throughout the growth cycle, but changes according to the developmental stage at application, indicating that timing is as important as dose in designing practical farmer recommendations.

3.3 Soil/Soaking Application Efficacy of Nano-Silica in Rice

Unlike the foliar pathway which relies on leaf uptake, application through the growing medium utilizes the root uptake pathway, either as a basal soil fertilizer, seed soaking before planting, or through irrigation water management that affects nano-silica availability in the root zone. Five studies in this review tested the soil/root application pathway with contexts generally more directed toward mitigating specific soil-based stresses, compared to the general growth improvement purpose more dominant in foliar studies. This difference in research orientation is itself an interesting initial finding, before moving to the quantitative comparison in Table 3.

Table 3: Summary of Studies on Soil/Soaking Nano-Silica Application Efficacy in Rice

Purpose Category	Reference	Key Findings
Yield improvement	Jin et al. [21]	Basal fertilizer 15 kg/ha, saline land; grain yield +23.3% and +33.3% in two varieties

Purpose Category	Reference	Key Findings
Heavy metal mitigation	Wang et al. [22]	Soil, 500 mg/kg under AWD irrigation; As decreased 29%, Cd decreased 68% simultaneously
	Ashraf et al. [11]	Hydroponic 50 μ M; root/shoot Cd uptake decreased 30.2%/15.8%
	Ghouri et al. [10]	Hydroponic 2.5 mM + Fe-NPs; shoot Pb content decreased 27%
Salinity tolerance	Ijaz et al. [16]*	Soil amendment (method needs verification); biomass increased, HKT gene expressed

Unlike the pattern in foliar application (Table 2) which is dominant for general growth purposes, Table 3 shows that soil/root application is more directed toward mitigating specific soil-based stresses, especially heavy metal toxicity, covering three of the five studies reviewed. This makes mechanistic sense: soil application allows nano-silica to interact directly with the soil-contaminant complex or be present in nutrient solution in direct contact with the root surface before heavy metals are translocated to upper plant tissue, consistent with the note by Rakesh et al. [2] regarding the role of nano-silica in soil-based stress mitigation. The study by Wang et al. [22] shows something particularly important: nano-silica's ability to mitigate two heavy metals simultaneously (arsenic and cadmium), which generally have different biological uptake pathways, making them difficult to control simultaneously through conventional approaches; the best effect was obtained not at the highest dose, but at a moderate dose (500 mg/kg) combined with alternate wetting and drying irrigation management, indicating that the interaction between dose and other cultivation practices is as important as the dose itself. Interestingly, Jin et al. [21] show that soil application is also effective for yield improvement under saline conditions, not just heavy metal mitigation. Important note: the application method of Ijaz et al. [16] has not been successfully verified with certainty from accessible sources despite repeated searches; please check directly with the original article before finalization, as this may affect its classification in Table 2 or Table 3..

3.4 Direct Comparison: Foliar vs. Soil/Root Application in the Same Study

Sections 3.2 and 3.3 show that foliar and soil application are equally effective, but the comparison between them is indirect since they come from different studies, with different varieties, environmental conditions, and measurement parameters. Such comparisons are prone to bias because differences in results could be caused by factors other than the application method itself. Much stronger methodological value is obtained from studies that test both application methods under the same experimental conditions, since confounding variables such as variety, soil conditions, and weather can be controlled. Four studies in this review meet this criterion, as summarized in Table 4 based on their testing context.

Table 4: Summary of Studies Directly Comparing Foliar vs. Soil/ Root Application in Rice

Testing Context	Reference	Key Findings
Disease resistance	Du et al. [23]	Foliar 100 mg/L vs root 2000–3000 mg/L, blast disease; high-dose foliar worsened disease, root more effective & safer
	Tan et al. [24]	Foliar vs root (VMSN), bacterial blight & sheath blight; foliar more strongly triggered systemic immunity
Salinity stress	Badawy et al. [25]	Seed soaking vs foliar; soaking superior for roots, foliar superior for leaf area
Normal conditions	Kheyri et al. [26]	Foliar vs soil (Si+Zn NPs), field conditions; foliar slightly superior to soil

The four studies in Table 4 produce interesting yet complex patterns. Kheyri et al. [26] under normal field conditions and Tan et al. [24] in the disease resistance context, despite targeting very different purposes, both found foliar application superior to root/soil. Conversely, Du et al. [23], also targeting disease resistance, found the opposite pattern — root application superior and safer than foliar. This difference between Du et al. [23] and Tan et al. [24], who both tested foliar vs root for rice disease resistance, is most likely caused by differences in nanoparticle design — conventional SiO₂NPs in the first study versus specially structured mesoporous silica nanoparticles (virus-like mesoporous silica nanoparticles/VMSN) in the second — rather than merely the disease type tested. This indicates that nanoparticle physical design can be a determining variable

equally important as the application pathway itself. Badawy et al. [25] add that method superiority also depends on the target parameter measured; seed soaking is superior for root parameters, while foliar is superior for canopy leaf parameters, so “which method is better” is an incomplete question without the context of “better for what purpose.” The collective conclusion from Table 4 — that no single application method is absolutely superior for all purposes and nanoparticle types — is the main synthesis contribution of this review and directly answers the objective formulated in the Introduction..

3.5 Role in Plant Stress Tolerance (Abiotic and Biotic)

Besides affecting growth and yield under normal conditions, nano-silica has also been widely tested for its role in helping rice cope with two main stress categories: abiotic stress from physical-chemical environmental factors such as salinity, drought, and heavy metal contamination, and biotic stress from pest organism attacks such as fungal and bacterial pathogens. Both categories are discussed sequentially here because they involve interrelated plant physiological defense mechanisms, although the trigger type and response differ.

On the abiotic stress aspect, salinity and drought are the two most significant productivity-limiting factors in sub-optimal land, while heavy metal contamination challenges former mining land and areas with industrial pollution history. Nine of the sixteen primary studies reviewed specifically target the abiotic stress context, making it the category with the most evidence among all topics discussed. A summary is presented in Table 5, grouped by stress type.

Table 5: Summary of Studies on the Role of Nano-Silica in Abiotic Stress Mitigation in Rice

Stress Type	Reference	Key Findings
Salinity	Jin et al. [21]	Soil application; grain yield increased under saline irrigation
	Alam et al. [19]	Foliar application; antioxidant activity increased
	Larkunthod et al. [12]	Foliar application; photosynthesis increased, H ₂ O ₂ decreased
	Ijaz et al. [16]	Soil application; HKT gene expression (Na ⁺ regulation) increased
	Badawy et al. [25]	Foliar + soaking; root & leaf parameters improved
Drought	Elshayb et al. [14]	Foliar application; growth & yield increased under 3 irrigation regimes
Heavy metals	Wang et al. [22]	Soil (500 mg/kg, AWD); As decreased 29%, Cd decreased 68%
	Ashraf et al. [11]	Hydroponic; Cd uptake decreased, antioxidants increased
	Ghouri et al. [10]	Hydroponic; Pb uptake decreased

Table 5 shows a fairly clear evidence imbalance between stress types: five studies target salinity, three target heavy metals, but only one study (Elshayb et al. [14]) explicitly targets drought stress, and even then as a secondary effect of comparing irrigation regimes rather than the main research focus. This imbalance is important given that drought is a significant rice cultivation challenge, particularly in upland (gogo) and rainfed lowland rice systems common in Indonesia. On the mechanism aspect, salinity and heavy metal studies consistently report three main pathways: increased antioxidant enzyme activity (superoxide dismutase, catalase, peroxidase) neutralizing free radicals from oxidative stress; regulation of ion homeostasis, particularly the Na⁺/K⁺ ratio in salinity through activation of transporter genes such as HKT as shown by Ijaz et al. [16]; and strengthening of the apoplastic barrier in root cell walls limiting toxic ion or heavy metal translocation from root to shoot. These mechanisms are consistent with the broader synthesis in Yan et al. [8] regarding nano-silica's role in plant stress alleviation. The drought stress evidence gap identified from Table 5 is one of the most concrete and contextually relevant recommendations for further research from this review's synthesis.

Different from abiotic stress originating from physical-chemical conditions, rice also faces significant biotic pressure from various pathogens, including fungi causing blast and brown spot disease, and bacteria causing bacterial leaf blight and sheath blight, which collectively can cause substantial yield loss if uncontrolled. Silicon has long been known to strengthen plants' natural defense systems against pathogens, and nano-silica is expected to provide a similar effect with higher efficiency. Four studies in this review tested nano-silica's role against rice disease, covering both fungal and bacterial pathogens, summarized in Table 6 by pathogen type.

Table 6: Summary of Studies on the Role of Nano-Silica in Biotic Resistance in Rice

Pathogen Type	Reference	Key Findings
Fungal	Gabr et al. [27]	Blast & brown spot; both diseases suppressed, yield components improved
	Du et al. [23]	Blast; appropriate foliar dose decreased severity ~70%, excessive dose worsened
Bacterial	Abdallah et al. [28]	Bacterial leaf blight; Ni-SiO ₂ nanocomposite suppressed growth & biofilm of <i>Xanthomonas oryzae</i>
	Tan et al. [24]	Bacterial blight & sheath blight; systemic nanoparticle migration, immunity activated, safe

The synthesis from Table 6 shows two important complementary points. First, mechanistic consistency among the four studies: all report involvement of induced defense pathways, either through salicylic acid signaling triggering systemic acquired resistance, or physical strengthening of the epidermal cell wall via silica deposition forming a barrier against pathogen penetration. Second, the range of pathogens tested is quite broad, covering both fungal [27], [23] and bacterial [28], [24] pathogens, indicating that nano-silica's protective benefits are cross-pathogen and not limited to one microorganism group. However, as discussed in section 3.4, the direction of the application method effect is inconsistent between Du et al. [23], who found root superior, and Tan et al. [24], who found foliar superior for disease resistance. This reaffirms that nanoparticle design, rather than merely the application pathway, appears to be a stronger determining variable for biotic protection success — an insight future researchers should consider when designing nano-silica studies for disease resistance. Overall, both abiotic and biotic stress in this section show the same common thread: nano-silica's efficacy against rice plant stress is highly contextual, depending on stress type, application method, and nanoparticle characteristics simultaneously

3.6 Dose, Safety Factors, and Practical Recommendations

Classical toxicology principles state that almost all substances, including beneficial nutrients, can become harmful when given in excessive concentrations, a phenomenon known as the hormesis response. This principle also applies to nano-silica, as shown by several studies in this review, which consistently report an optimal dose threshold that, when exceeded, causes adverse effects instead of additional benefits to rice plants. Understanding this threshold is practically crucial, since overly conservative dose recommendations risk not providing optimal benefits, while excessive doses risk being counterproductive and wasteful. A summary of findings on excessive dose is presented in Table 7 by finding direction.

Table 7: Summary of Studies on Excessive Dose and Adverse Effects in Rice

Finding Direction	Reference	Key Findings
Adverse effects of excessive dose	Patil et al. [13]	>125 ppm (seed soaking); seed quality parameters decreased
	Jiang, Y. et al. [17]	200 mg/L non-nano Na-silicate; shoot biomass -27 to -51%, root -4 to -17%
	Du et al. [23]	100 mg/L foliar; blast disease severity actually increased
Safe profile	Tan et al. [24]	Excessive foliar (VMSN); no toxicity found, contrasting with the three other studies

Three of the four studies in Table 7 show the same and mutually reinforcing pattern: excessive nano-silica dose, or even non-nano silica as a comparison in Jiang, Y. et al. [17], is consistently associated with adverse effects — decreased seed quality, decreased shoot and root biomass, or increased disease severity that should have been suppressed. This shows the dose-response relationship of nano-silica in rice is non-linear, not a “more is better” relationship often mistakenly assumed in field fertilization practices. However, Tan et al. [24], contrasting with the other three studies, found no toxicity even at excessive foliar application, showing that nano-silica's safety profile greatly depends on nanoparticle design, not merely absolute concentration. The VMSN nanoparticles used by Tan et al. [24] likely have controlled-release characteristics different from conventional SiO₂NPs, avoiding excessive accumulation in target tissue within a short time. The practical

implication is that nano-silica dose recommendations for rice cannot be a single generalization, but need to be formulated specifically for purpose, application method, and nanoparticle type.

Overall, the synthesis from the seven tables above shows four main interrelated patterns. First, foliar application (Table 2) is more recommended for general vegetative growth and yield improvement under normal or mild-stress conditions, given the ease of application and speed of response offered. Second, soil/root application (Table 3) is more recommended for mitigation contexts rooted in soil conditions, especially heavy metal toxicity, since this pathway allows direct interaction with the contaminant source before translocation to the consumed plant part. Third, no application method is absolutely superior for all purposes (Tables 4 and 6), because nanoparticle design also determines the final outcome, and can even reverse findings between studies testing similar contexts. Fourth, dose safety is context-specific rather than a single generalization (Table 7), so practical dose recommendations need to consider application purpose, method, and nanoparticle characteristics simultaneously. The drought stress evidence gap identified in Table 5 is the most urgent further research direction for rice cultivation in drought-prone regions such as Indonesia, given that currently available empirical evidence remains far from adequate to support evidence-based application recommendations in that context

4. Conclusion

This literature review shows that nano-silica has great potential as an alternative fertilizer for rice, both through foliar and soil application, with different efficacy patterns depending on the agronomic objective. Foliar application is generally superior for improving vegetative growth and yield under normal or mild-stress conditions, while soil/root application is superior for mitigating specific soil-based stress, particularly heavy metal toxicity. However, no single application method was found absolutely superior for all purposes, since nanoparticle design also determines the direction of outcomes and can even reverse findings between studies testing similar contexts, particularly regarding disease resistance. Dose safety was also shown to be context-specific, with an optimal threshold that, when exceeded, can cause adverse rather than additional benefits. Thus, application method and dose recommendations for nano-silica in rice need to be formulated specifically for purpose, method, and nanoparticle type, rather than as a single generalization. Further research is recommended to focus on three main directions: testing nano-silica efficacy against drought stress, which remains minimally discussed in existing literature; standardization of nano-silica characterization and dosing across studies for more valid comparability; and large-scale field trials on various local Indonesian rice varieties to validate findings that are so far dominated by pot-scale and greenhouse research.

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