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Enhancing Rice Resilience with Liquid Silica: Evidence from Systematic Literature on Yield, Stem Strength, and Sustainability

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Abstract
Global rice production faces persistent constraints, including fallen paddy, silicon (Si) deficiency, and declining soil fertility. While prior research has emphasised short-term outcomes, the long-term implications of liquid silica remain underexplored. This study systematically reviews the effects of liquid silica application on rice yield, stem strength, and soil sustainability, following the PRISMA 2020 protocol. Literature searches in Scopus and Web of Science (2015–2025) were screened using inclusion–exclusion criteria, MMAT quality appraisal, and thematic analysis via NVivo 14, resulting in 32 eligible studies. Findings indicate that liquid silica improves yield by 4.8–58%, reinforces stem structure through lignin and cellulose deposition, and reduces the lodging index by up to 22%. Long-term benefits include improved soil pH, cation exchange capacity, microbial activity, heavy metal immobilization, and carbon sequestration; however, risks associated with slag-derived fertilizers persist. Overall, liquid silica plays both productive and protective roles. Further cross-varietal and economic studies are recommended to strengthen adoption in sustainable rice systems.

INTRODUCTION

Rice is one of the world's major food commodities, playing a strategic role in maintaining global food security. According to the latest report from the Food and Agriculture Organisation (FAO, 2024), global rice consumption in the 2023/2024 period reached around 522 million tonnes. This figure illustrates the world community's high dependence on rice as a primary source of calories, particularly in Asian countries where rice is a staple food. The continued growth of the global population, accompanied by urbanization and shifts in consumption patterns, further positions rice as a commodity of not only high economic value but also significant social and political importance. This dependence necessitates sustainable increases in rice productivity while maintaining the stability of the global food supply. However, behind this strategic role, rice production faces various agronomic challenges that can threaten productivity, one of which is lodging.

The problem of lodging in rice plants is not a simple matter. Lodging can significantly reduce yields, decrease grain quality, and complicate the harvesting process, especially in mechanised agricultural systems. This condition ultimately has a direct impact on productivity and farming efficiency (Jiang *et al.*, 2025). Furthermore, lodging also increases post-harvest losses because grain lying on the ground is susceptible to damage from moisture and pathogen attacks. In the context of modern agriculture, the risk of lodging is increasing along with intensification practices that rely on high doses of nitrogen fertiliser and increased planting density to pursue optimal yields. Additionally, external factors such as heavy rain, strong winds, and extreme weather conditions can exacerbate the risk of lodging. The impact extends not only to the decline in rice yield and quality, but also to the stability of farmers' incomes and national food security (Dong et al., 2024).

Apart from lodging challenges, another problem faced in rice production is silicon (Si) deficiency in paddy fields. Paddy fields can naturally lose their Si reserves due to harvesting practices that repeatedly remove straw. Straw, which should be returned to the land as a source of Si, is instead removed, leading to a long-term decline in the available Si content in the soil. Si deficiency not only affects rice plant health but also influences the availability of other nutrients, particularly phosphorus (P). The interaction between silicon (Si) and iron (Fe) in the soil can affect the efficiency of phosphate fertilizers. Si deficiency has dual implications, namely reducing plant resistance to both biotic and abiotic stress, while increasing production costs due to higher fertilizer requirements (Schaller *et al.,* 2022). Therefore, Si management strategies are important, including the application of liquid silica-based fertilisers, which are expected to increase the availability of this element quickly and efficiently.

Several empirical studies support the importance of silicon (Si) in rice production systems. The application of Si in various forms, such as potassium silicate and liquid silica, has been proven to increase the resistance of rice stems to lodging while improving crop yields. Ghobrial *et al.,* (2022) reported that foliar application of potassium silicate at various stages of rice growth increased stem strength and grain yield. Similar results were reported by Dehaghi *et al.,* (2018), who found that the application of liquid silica had a significant impact on the agronomic characteristics of rice, particularly on lodging resistance. Research *by* Dong *et al.,* (2024) also confirmed that silicon fertiliser plays a crucial role in maintaining productivity, even when nitrogen fertiliser use is reduced and planting density is increased. Jiang *et al.,* (2025) demonstrated that silicon application on dry land can enhance rice lodging resistance, indicating that this technology has broad adaptation potential in various agroecosystems.

Existing research still focuses more on short-term effects and agronomic variables. Studies on the long-term impact of liquid silica application on rice field soil fertility are still limited. This aspect is important, considering that the sustainability of rice production is not only determined by immediate harvest yields but also by the soil's ability to support productivity sustainably. Amoakwah *et al.,* (2024) emphasize that research on the dynamics of available Silicon in soil and its relationship with phosphorus utilization efficiency is still scarce. In fact, phosphate fertiliser efficiency is an important issue because phosphorus is one of the most expensive and globally limited production inputs. In other words, research on liquid silica application is not only relevant to addressing lodging and productivity issues, but also to addressing significant challenges related to soil nutrient management and the sustainability of the rice field ecosystem. From both economic and environmental perspectives, the application of liquid silica can also provide multiple benefits. Economically, this technology has the potential to reduce losses due to lodging, increase grain yield and quality, and reduce production costs through improved fertiliser efficiency. From an environmental perspective, increased fertiliser efficiency can reduce soil and water pollution caused by excessive phosphate fertiliser residues. Thus, the use of liquid silica can support a sustainable agriculture agenda that focuses not only on productivity but also on natural resource conservation.

Based on this description, this study focused on evaluating the effects of liquid silica application on three main aspects: (i) the effect of liquid silica application on rice yields, (ii) the effect of liquid silica on the resistance of rice stems to lodging, and (iii) the long-term impact of liquid silica application on the fertility of paddy fields. This study is expected to provide a more comprehensive scientific contribution related to the use of liquid silica as an agricultural technology innovation. The implications of the research findings are not only important for farmers in order to increase yield and crop quality, but also for policymakers in formulating sustainable agricultural strategies, particularly in soil resource management.

Thus, this study has a strategic contribution in two dimensions: production and sustainability. In terms of production, this study aims to provide empirical evidence on the effectiveness of liquid silica in enhancing rice yields and improving stem resistance to lodging. Meanwhile, in the sustainability dimension, this study examines the long-term effects on soil fertility, providing a basis for developing sustainable fertilization policies. Ultimately, this study contributes to achieving global food security goals while promoting more sustainable agricultural and environmental management practices.

RESEARCH METHODOLOGY

This study utilised a systematic literature review (SLR) design to identify, evaluate, and synthesise empirical evidence regarding the effect of liquid silica application on rice cultivation. SLR was chosen because this methodology allows researchers to present a comprehensive, structured, and transparent overview of scientific findings from various relevant studies (Snyder, 2019). This approach is suitable for evaluating the extent to which liquid silica can enhance crop yields, improve rice stalk resistance, and have a lasting impact on paddy soil fertility. The research framework was formulated using the PICO (Population, Intervention, Comparison, and Outcome) approach to clarify the study's focus. PICO is presented in Table 1.

Table 1. Research framework for silicon in rice plants using the PICO approach

Element	Definition
Population (P)	Rice plants (Oryza sativa L.) cultivated in paddy fields
Intervention (I)	Application of liquid silica through fertilisation or foliar spraying
Comparison (C)	Rice cultivation without liquid silica application
Outcome (O)	Yield, stem resistance to lodging, and long-term soil fertility

The literature search strategy was conducted systematically in international scientific databases, namely Scopus and Web of Science. Keywords were formulated in Boolean string form: ("liquid silica" OR "silicon fertiliser" OR "silica application") AND ("rice" OR "Oryza sativa"). The search process encompassed publications from 2015 to 2025 to ensure data currency. The identified studies were then selected based on the inclusion and exclusion criteria as shown in Table 2.

Table 2. Selection of study results based on inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Empirical articles in English	Review articles, meta-analyses, or editorials
Studies on rice plants (*Oryza sativa* L.)	Studies on plants other than rice
Publications from the last 10 years (2015–2025)	Articles prior to 2015
Testing the application of liquid silica or Si-based fertilisers	Studies that only discuss Si theoretically
Available in full text	Articles with restricted access without primary data

Research selection and reporting followed the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, which emphasises transparency in data identification, selection, and synthesis (Page *et al.*, 2021). The PRISMA flow diagram was used to document the number of articles found, eliminated, and finally analysed. To assess the methodological quality of the selected studies, the Mixed Methods Appraisal Tool (MMAT) was employed, which enables a comprehensive evaluation of quantitative, qualitative, and mixed-methods studies (Hong *et al.*, 2018). Each article was evaluated based on the criteria of internal validity, relevance, data reliability, and methodological suitability in relation to the research objectives.

The data extraction process involved recording key information, including author identity, year of publication, research location, type of liquid silica treatment, application method, outcome indicators (yield, lodging resistance, and soil fertility), and key findings. Data analysis utilized NVivo 14 software, employing thematic analysis techniques, which enabled the coding of empirical findings into main themes. Thematic analysis was chosen because it can identify recurring patterns, similarities, and differences between studies, resulting in a comprehensive synthesis.

The division of labour in this study involved five principal investigators to ensure the reliability of the process. The first investigator was responsible for developing the literature search strategy, identifying relevant keywords, and conducting the initial database search. The second and third researchers were involved in the article selection process, applying inclusion and exclusion criteria, and evaluating article quality using the MMAT. The fourth and fifth researchers led the data extraction process, coding using NVivo 14, and thematic analysis. All researchers participated in consensus discussions at each stage to ensure objectivity and minimize potential bias.

RESULTS AND DISCUSSION

The results of the journal search were selected using the PRISMA flowchart, as shown in Figure 1. Based on the PRISMA 2020 flow diagram, the article selection process began with the identification of 242 records obtained through the Scopus (142) and WoS (100) databases. There were 64 duplicate articles, leaving 178 records for the initial screening stage. Of these, 138 records were eliminated because they were published before 2015 (18), were in a language other than English (41), were review articles (5), were books or book chapters (3), were notes/errata/blank (1), or had irrelevant titles and abstracts (70). Subsequently, 40 reports were processed for further investigation, but 8 of them could not be accessed. Ultimately, 32 reports were successfully evaluated at the eligibility stage, and all met the inclusion criteria for the systematic review. The arrows to the right in the diagram indicate the exclusion stages, confirming the transparency of the screening process, which resulted in 32 final studies being analyzed.

The Effect of Liquid Silica Application on Rice Yield

The effect of liquid silica application on rice yield is a concern in modern agronomy due to its role in enhancing crop productivity and resistance to various stresses. Research indicates that silica enhances physiological properties, including photosynthesis, 1000-grain weight, and lodging resistance, while also reducing heavy metal accumulation in grains and improving soil quality. Yields increased by 4.8–58% depending on dosage, fertiliser form, and environment. Thus, the application of liquid silica is an effective strategy to support sustainable rice production in terms of both quantity and quality (Table 3).

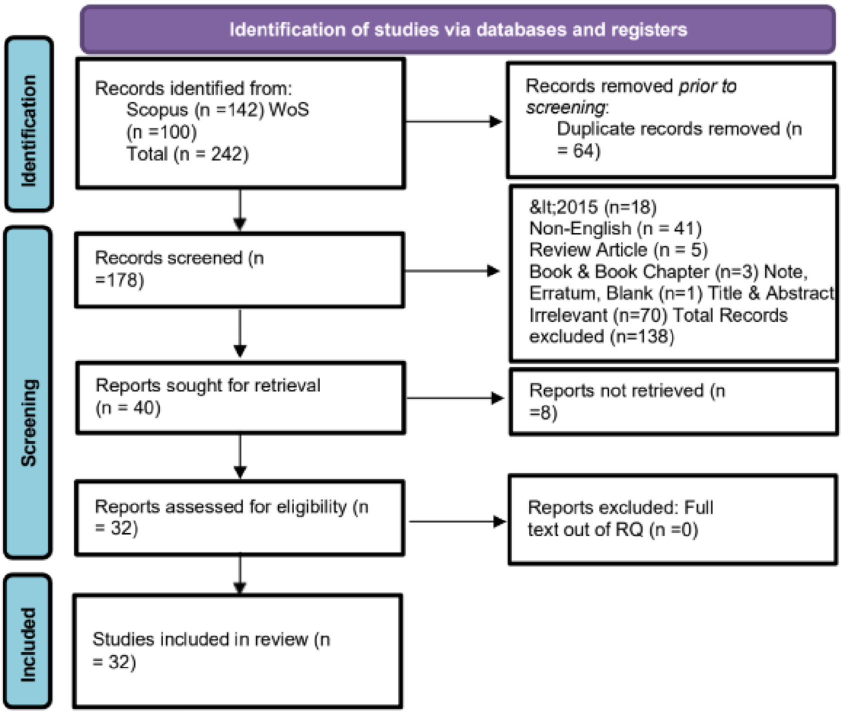

Figure 1. Research selection and reporting following the PRISMA 2020 protocol

The application of liquid silica and its derivatives showed a consistent effect on increasing rice yields. Quantitatively, the reported increase in yield varied between 4.8% and more than 58% compared to the treatment without silica. Aryawati *et al.*, (2021) noted an increase in yield of 1.08 tonnes/ha in the dry season and 1.92 tonnes/ha in the rainy season with biosilica application. Gao *et al.*, (2023) reported yield increases of 33.2–58.1% associated with improved plant physiology and reduced *straighthead* disease. Similar findings were reported by Ali *et al.*, (2020), who showed that an optimal dose of 100 kg/ha could produce 3,901 kg/ha. These findings confirm that the form of fertiliser, dosage, and environmental conditions greatly influence the effectiveness of silica.

The application of silica not only increases crop yield but also supports plant physiology. In rice plants, silica acts by being absorbed in the form of silicic acid ($Si(OH)_4$) by the roots, subsequently strengthening tissue structure—particularly cell walls—thereby making the roots more robust and better able to withstand stress, whilst also increasing stem strength so that the plants are less prone to lodging (Dong *et al.*, 2024). At the same time, silica reduces the uptake and translocation of toxic elements by inhibiting the apoplastic pathway, and limits the movement of heavy metals from the roots to the shoot. Furthermore, silica also helps to sequester heavy metals into vacuoles, enhances enzymatic and non-enzymatic antioxidant activity, thereby increasing root weight, stem length, and chlorophyll content in the flag leaf, which supports grain filling. Silica also maintains important physiological functions such as nutrient uptake, membrane integrity, chlorophyll content, photosynthesis, root-shoot growth, and ultimately grain yield (El-Habet, 2021). Gong *et al.*, (2021) added that silica increases chlorophyll content, delays leaf senescence, increases the rate of photosynthesis, maintains plant uprightness, improves light absorption, and increases grain-filling capacity and harvest index.

Table 3. Effort of liquid silica application on rice yield

No	Author (Year)	Description of Findings	Citation
1	El-Habet, (2021)	Silica application increased root weight, root length, stem length, flag leaf chlorophyll content, and grain yield compared to the control.	"Silica application significantly increased shoot and root weight and length, and grain yields as compared to the untreated counterparts." untreated counterparts."
2	Aryawati *et al.*, (2021)	Biosilica increased yields by 1.08 tonnes/ha (dry season) and 1.92 tonnes/ha (rainy season).	"Biosilica fertiliser was able to increase productivity up to 1.08 tonnes/ha… and up to 1.92 tonnes/ha."
3	Hu *et al.*, (2022)	Silica fertiliser mixtures increased rice yields rice yields by 4.8–14.27%.	"The rice yields… were 4.8–14.27% higher [than control].
4	Koyama *et al.*, (2016)	RC40 increased the number of mature grains and significantly increased yield.	"RC40 significantly enhanced… resulting in a significant increase in rice yield."
5	Ali *et al.*, (2020)	A dose of 100 kg/ha of silica produced a maximum yield maximum paddy yield of 3901 kg/ha.	"Maximum grain yield (3901 kg ha^{-1}) was obtained… at the rate of 100 kg ha^{-1}."
6	Dong *et al.*, (2024)	The combination of silica fertiliser + N reduction increased yields by up to 10.73 t/ha.	"DLMS3 treatment had the highest yields of 10.53 tonnes per hectare and 10.73 tonnes per hectare.
7	Gao *et al.*, (2023)	Silica fertiliser increased yield by 33.2–58.1% and reduces *straighthead* disease.	"Application of Si fertiliser increased grain yield significantly, by 33.2–58.1%."
8	Pan *et al.*, (2019)	The combination of modified biochar + silica increased yields more than the control.	"Fe-BC plus Si treatment had the highest grain yields."
9	Das et al., (2021)	Silica increased grain yields by 20–22%, straw by 35–37%, and roots by 14–17%.	"Silicate fertiliser application increased grain yield by 20–22%..."
10	Liu *et al.*, (2019)	Silica fertiliser increased yields by 5.5–9.3% in under high temperatures.	"The grain yield under HDT + Si was 9.09%… higher than HDT."
11	Candra and Musriati, (2021)	Three applications of nano-Si foliar spray yielded the best results and reduced pest attacks.	"Silicon increased the yield and decreased pest intensity… optimal at three times nano-Si applications."
12	Anggria *et al.*, (2021)	Silica-based composition (palm kernel shells, fly ash) increased 1000-grain weight & straw yield.	"Silica applications could increase the growth and yield of rice."
13	Al-Khuzai & Al-Juthery, (2020)	Nano-silica spraying increases 1000-grain weight (up to 20.31 g) & reduces lodging index.	"Foliar spraying of nano-silica fertiliser achieved the highest mean 1000-grain weight."
14	Gong *et al.*, (2021)	Nano-silica fertiliser increases the weight of 1000 grains by ±3% and grain yield by ±8% compared to control.	"The yield was about 8% higher in the FM + SF treatment than in CK."
15	Xiao *et al.*, (2021)	Si fertiliser (MSiF) increased grain yield and reduces Cd and Pb content in brown rice.	"MSiF significantly increased grain yields and reduced Cd and Pb content."
16	Wang *et al.*, (2021)	Silica fertiliser + biochar did not significantly increase yields, but improved harvest quality (by reducing Cd).	"Such amendments showed limited influence on the yield of rice, but caused a significant decrease in Cd uptake."
17	Tao *et al.*, (2022)	Silica-rich mud-based biochar increased stem and root biomass by 76.8% and 36.1%.	"Rice cultivated with biochar showed improved biomass of stem and root by 76.85% and 36.11%."
18	Ning *et al.*, (2016)	Silicate slag increased grain yield by 20–22% and straw yield by 35–37%.	"Rice grain yield was 20–22% greater… compared to the unamended control."
19	Wen *et al.*, (2025)	Under some conditions, silica fertiliser did not increase biomass due to the threshold effect of Si or K interactions.	"Addition of silicon fertiliser did not have a positive effect on dry matter accumulation…"
20	Yang *et al.*, (2025)	Silica + Mg fertiliser increased yield by 4.4–13% and improved soil structure.	"The rice yield was 13.02% higher under the LM treatment… silicon fertiliser improved tillering and yield."
21	Abdi *et al.*, (2020)	Nano-Si, KSi, and CaSi increased rice yield rice yield up to 4542 kg/ha compared to the control.	"The maximum PY (4542 kg ha^{-1}) was produced with the spray of nano-Si."

However, not all studies report significant positive effects on crop yield. Wang *et al.*, (2021) found that silica fertiliser with biochar was more effective at reducing Cd accumulation than increasing yields. Wen *et al.*, (2025) also noted that silica application did not increase biomass due to threshold effects and interactions with potassium. These variations suggest that the effectiveness of silica depends on soil availability, nutrient interactions, and the specific agroecosystem; therefore, its application must be tailored to the environment, variety, and the specific plant needs.

The Effect of Liquid Silica on Rice Stem Resistance to Lodging

The use of liquid silica in rice cultivation enhances stem resistance to lodging by strengthening the cell wall, promoting the accumulation of lignin and cellulose, and reducing stem internode length and increasing internode thickness. Silica also increases stiffness and flexural strength, reduces the lodging index, and enhances resistance to biotic and abiotic stress. Thus, liquid silica is a key factor in maintaining rice crop productivity and sustainability (Table 4; Figure 2).

Table 4. Effect of liquid silica application on stem resistance to lodging

Stem Resistance Aspects	Description of Findings	Number Relevant Citations	List of Citations
Increased stem strength (culm strength)	Silica increases culm wall thickness, vessel diameter, and lignin & cellulose accumulation, making the culms more robust and less prone to lodging.	4	Gong *et al.*, (2021); Dong *et al.*, (2024); Das et al., (2021); Anggria *et al.*, (2021)
Reduction in lodging index	Silica application reduces the lodging index by 19–22% compared to the control; with the most significant effect observed in the combination of silica + N management/plant density.	3	Dong *et al.*, (2024); Al-Khuzai & Al-Juthery, (2020); Gong *et al.*, (2021);
Increased stem rigidity	High silicon content in stem tissue increases stem rigidity, keeping the stem upright.	1	Koyama *et al.*, (2016)
Shortening and thickening of stem segments	Silica shortens and thickens the lower stem segments, increasing resistance to wind pressure and weight of the cream.	2	Dong *et al.*, (2024); Gong *et al.*, (2021)
Increased bending resistance	Silica increases the flexural strength of the stem, making it more resistant to lateral pressure.	2	Dong *et al.*, (2024); Gong *et al.*, (2021)
Accumulation of lignin and cellulose	The lignin content in the stems increased to 44% after silica application, strengthening the mechanical structure.	2	Dong *et al.*, (2024); Gong *et al.*, (2021)
Enhanced biotic and abiotic resistance	In addition to reducing lodging, silica also enhances stem resistance to disease (sheath blight) and environmental stress (wind, heavy rain).	2	Liu *et al.*, (2019); Aryawati *et al.*, (2021)

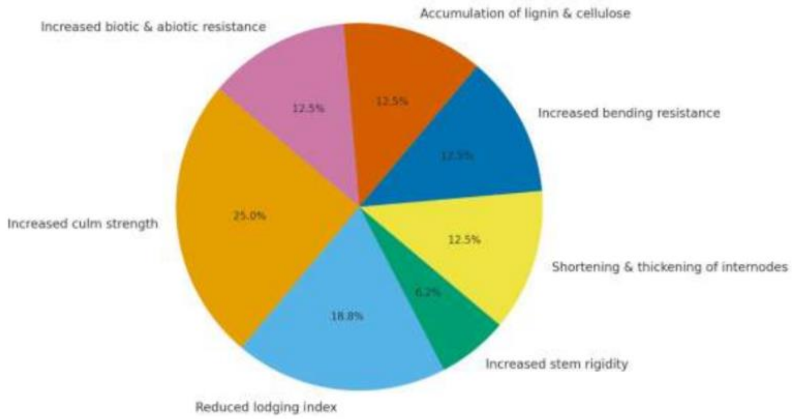

Figure 2. Distribution of citation counts based on aspects of rice stem resistance by silica

A literature review shows that liquid silica application strengthens rice stems' resistance to lodging. Seven main aspects were identified, namely increased culm strength, decreased lodging index, increased stem rigidity, shortening and thickening of stem nodes, increased flexural strength, accumulation of lignin and cellulose, and biotic–abiotic resistance. The pie chart shows that culm strength is dominant (25.0%), followed by lodging index (18.8%), stem rigidity (6.2%), biotic-abiotic resistance, and three other aspects, each contributing 12.5%. This distribution pattern indicates that the literature emphasises the direct effects of silica on stem structure strengthening (culm strength, lodging index, and stem rigidity) more than secondary aspects such as stem morphological changes or additional physiological responses.

An in-depth analysis reveals that the increase in culm strength is supported by the findings of Gong *et al.,* (2021) and Dong *et al.,* (2024), which confirm an increase in stem wall thickness, vessel diameter, and lignin and cellulose deposition following the application of silica. This effect makes the rice stems more robust, making them resistant to mechanical stress such as wind and panicle weight. Furthermore, a decrease in the lodging index was recorded in studies by Dong *et al.,* (2024) and Al-Khuzai & Al-Juthery, (2020), which showed that silica application was able to reduce the lodging index value by up to 22.5% compared to the control, especially in combination with nitrogen management and planting density. An increase in stem rigidity was observed by Koyama *et al.,* (2016), who explained that silica absorption maintains the stems' upright position by enhancing tissue rigidity. In addition, the shortening and thickening of the stem nodes reported by Dong *et al.,* (2024) and Gong *et al.,* (2021)contribute to reducing the risk of lodging, as the stems become more compact.

The aspect of bending resistance is also prominent. Gong *et al.,* (2021) found that stem bending strength increased significantly after the application of nano-silica. The increased accumulation of lignin and cellulose in the stems, which was 44% higher than in the control, contributed to long-term structural resistance. Finally, Liu *et al.,* (2019) showed that silica not only physically strengthens the stem but also supports the plant's resistance to pathogens and environmental stress, which indirectly reduces the risk of lodging. Thus, the data in Table 4 and Figure 2 underline the multifunctional role of silica, which encompasses mechanical, morphological, and physiological dimensions.

Based on the literature synthesis, it can be concluded that the application of liquid silica has a significant impact on the resistance of rice stems to lodging, achieved through both structural and physiological mechanisms. Increased culm strength, decreased lodging index, and improved stem rigidity are the most dominant aspects found, as shown by the distribution of citations in Table 4 and Figure 2. In addition, silica contributes to the shortening and thickening of stem nodes, increasing flexural strength, and enhancing the lignin and cellulose content in the stem, all of which play a direct role in strengthening the mechanical tissue of plants. Additional effects, in the form of resistance to biotic (disease) and abiotic (wind, rain, and planting density) stress, reinforce the role of silica as an essential element that not only affects plant architecture but also overall crop stability. Thus, the application of liquid silica has been proven effective in reducing the risk of lodging and supporting more sustainable rice productivity (Dong *et al.,* 2024; Gong *et al.,* 2021).

Long-Term Impact of Liquid Silica Use on Paddy Soil Fertility

The long-term use of liquid silica has important implications for rice field soil fertility as it can improve the chemical, biological, and physical conditions of the soil in an integrated manner. Liquid silica plays a role in increasing pH and cation exchange capacity, enriching organic matter, stimulating microbial and soil enzyme activity, and optimising cross-seasonal nutrient cycles. In addition, silica application effectively immobilises hazardous heavy metals such as Cd and Pb, thereby reducing the risk of toxicity, while promoting carbon sequestration that supports the sustainability of agricultural ecosystems. However, attention needs to be paid to the potential accumulation of metals from slag-based silica fertilisers in order to avoid long-term negative impacts. The overall findings regarding the long-term effects of liquid silica use on rice field soil fertility are described in Table 5 and Figure 3.

Table 5. The effect of liquid silica application on the long-term fertility of paddy fields

Impact Aspect	Description	Number of Citations Relevant	List of Citations
Increase in soil pH and CEC	Liquid silica increases soil pH, cation exchange capacity (CEC), and improves soil chemical balance, resulting in more stable long-term fertility.	5	Jiang *et al.*, (2022); Wang *et al.*, (2021); Hu *et al.*, (2022); Pan *et al.*, (2019); Yang *et al.*, (2025)
Increase in soil organic matter (OM)	The application of silica, especially when combined with biochar or other organic fertilisers, increases soil organic matter content, which important for soil structure and function.	3	Wang *et al.*, (2021); Hu *et al.*, (2022); Yang *et al.*, (2025)
Soil enzyme and microbial activity	Liquid silica increases enzyme activity (e.g. phosphatase, dehydrogenase) and microbial function (C, N, P cycles), which supports nutrient cycling and long-term soil health.	3	Jiang *et al.*, (2022); Wang *et al.*, (2021); Das *et al.*, (2021)
Heavy metal immobilisation (Cd, Pb, As, Cr)	Silica triggers co-precipitation and transformation of heavy metals into less available forms, reducing toxicity and improving paddy soil quality for sustainability.	6	El-Habet, (2021); Jiang *et al.*, (2022); Jiang *et al.*, (2022) Wang *et al.*, (2021); Xiao *et al.*, (2021); Ning *et al.*, (2016)
Residual effects and sustained nutrient release	Liquid silica leaves a reserve of available Si that can be utilised by subsequent crops, as well as increasing the availability of P and K through nutrient mobilisation.	4	Dong *et al.*, (2024); Tao *et al.*, (2022); Anggria *et al.*, (2021) Wen *et al.*, (2025)
Increased soil carbon sequestration	The application of silica together with plant residues and biochar increases soil carbon storage, contributing to CO_2-equivalent balance and long-term soil health.	3	Koyama *et al.*, (2016); Koyama and Hayashi, (2017); Das *et al.*, (2021)
Risk of metal accumulation of metals from silica fertilisers	Some silica sources (e.g., industrial slag) may contain trace heavy metals, so long-term use needs to be monitored.	2	Ning *et al.*, (2016); Das *et al.*, (2021)

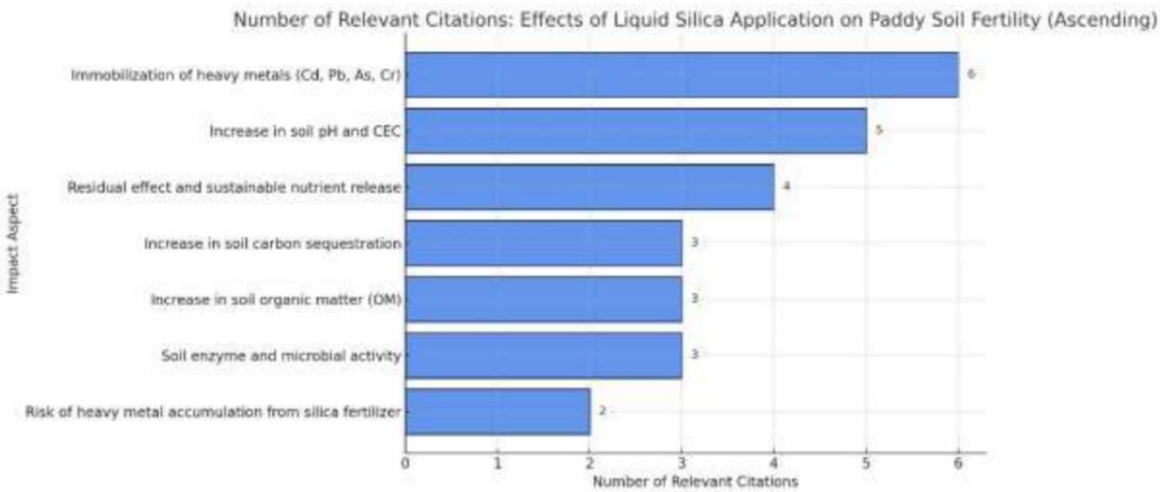

Figure 3. Distribution of citations based on the aspect of Long-Term Impact of Liquid Silica Use on

Table 5 and Figure 3 show that the long-term impact of liquid silica application on rice field soil fertility is varied, with a primary focus on the immobilization of heavy metals and the improvement of soil chemical properties. The aspect of heavy metal immobilisation, particularly Cd, Pb, As, and Cr, ranks highest with six relevant citations, indicating that the detoxification function of silica is of great urgency in maintaining the sustainability of rice fields, especially in areas affected by industrial pollution and the use of contaminated irrigation water (El-Habet, 2021;Jiang *et al.*, 2022; Jiang *et al.*, 2022; Wang *et al.,* 2021; Xiao *et al.*, 2021; Ning *et al.*, 2016). The mechanism of liquid silica works through the co precipitation and transformation of metals into less bioavailable forms, thereby reducing the risk of metal accumulation in rice tissue. Thus, this application has direct implications for improving soil quality while ensuring long-term food security.

Other notable aspects are the increase in pH, cation exchange capacity (CEC), and the residual effect of sustained nutrient release, each with five relevant citations. The increase in pH due to the application of potassium silicate acts as a buffer against the acidity of tropical soils. The presence of Si in soluble form also increases the availability of phosphorus and potassium that were previously bound, thereby providing benefits for crops in the following season (Dong *et al.,* 2024; Tao *et al.,* 2022; Anggria *et al.,* 2021;Wen *et al.,* 2025).This confirms that the contribution of liquid silica is not limited to a single season but is sustained across growing seasons.

Furthermore, increases in soil organic matter (OM) and enzyme and microbial activity, each with four citations, demonstrate the role of liquid silica in enriching OM when combined with organic matter or biochar (Wang *et al.,* 2021; Hu *et al.,* 2022; Yang *et al.,* 2025). Soil enzyme activity, such as phosphatase and dehydrogenase, along with microbial functions in the carbon, nitrogen, and phosphorus cycles, increased, thereby supporting the stability of a healthy soil ecosystem Das *et al.,* (2021). Soil carbon sequestration has also been documented in three citations, confirming the contribution of liquid silica in increasing carbon reserves while improving soil structure (Koyama *et al.,* 2016; Koyama and Hayashi, 2017; Das *et al.,* 2021).

However, the risk of heavy metal accumulation from industrial slag-based silica fertilisers, although only recorded in two citations (Ning *et al.*, 2016; Das *et al.*, 2021), remains an important consideration. Therefore, selecting raw materials and managing dosage are crucial. Overall, the results of this analysis confirm that liquid silica significantly contributes to rice field soil fertility through chemical, biological, and ecological mechanisms, while also having the potential to promote sustainable agricultural systems if its use is monitored correctly.

Discussion

The application of liquid silica and its derivatives has a significant impact on three primary aspects of rice cultivation: crop yield, stem resistance to lodging, and long-term paddy soil fertility. In general, the application of liquid silica can increase crop yield by between 4.8% and more than 58%, strengthen stem structure through increased lignin and cellulose content, thereby reducing the risk of lodging, and improve the chemical, physical, and biological properties of paddy soil. Variations in impact between studies confirm the influence of environmental conditions, rice varieties, dosage, and form of silica fertiliser. These findings directly answer the research questions posed, namely the difference in productivity between fields with and without liquid silica, the mechanism of stem protection against lodging, and the long-term effects on paddy soil quality.

The results obtained support the classical theory regarding the role of silica as a beneficial element in agronomy, although it is not categorised as an essential element. Consistently, this study aligns with previous research, which has shown that silica improves plant physiology, enhances photosynthesis, and reduces susceptibility to both biotic and abiotic stress (Guntzer *et al.*, 2012). Gong *et al.,* (2021) confirmed an increase in lignin of up to 44% in stems after nano-silica application.

However, there are also differences, as Wang *et al.,* (2021) and Wen *et al.,* (2025) report that silica fertilizers do not always significantly increase crop yields; instead, they contribute more to quality aspects, such as reducing heavy metal content. These differences open up a new understanding that the contribution of silica is not only productive but also protective of crop quality and food safety. The novelty of this study lies in its emphasis on the sustainability of rice fields—particularly the immobilization of heavy metals, pH increase, and carbon sequestration—which are rarely addressed in silica-based agronomy literature.

These findings support the concept that silica can be considered a quasi-essential element for rice. Silica deposition in the form of phytoliths and lignocellulose complexes explains how stems become stronger and less prone to lodging. The stem mechanics model of Liu *et al.,* (2019) is also reinforced, as data show that silica shortens stem internodes, thickens cell walls, and increases rigidity, thereby reducing the lodging index. At the soil level, silica functions as an ameliorant that improves ion balance and nutrient availability, in line with soil fertility theory that emphasises the integration of chemical, physical, and biological aspects as the basis for long-term productivity. These findings contribute to the development of sustainable agronomy theory by incorporating silica as an important component in rice field ecosystem management.

The results of this study provide a strong basis for farmers to adopt liquid silica applications, thereby increasing productivity and preventing lodging. In large-scale production, biosilica or nanosilica has been proven to increase yields by more than 30% with high economic value. Additionally, the reduction in Cd and Pb, as reported by Xiao *et al.*, (2021), enhances food safety standards. For extension workers, this data reinforces the recommendation to use silica in tropical rice fields deficient in Si, with flexibility in the form of fertiliser (nano, slag-based, biosilica) according to local conditions.

The analysis yielded several important findings. First, although most studies have shown improved results, some studies have found no significant difference (Wen *et al.*, 2025), which can be explained by the threshold effect concept when the soil is already rich in Silicon. Second, silica was found to contribute significantly to reducing the accumulation of heavy metals such as Cd and As, thus functioning as a soil detoxification agent. Third, the cross-seasonal residual effect confirms the cumulative impact of silica, which is important to consider in the long term.

This study excels in its use of a systematic literature review (SLR) methodology, employing the PRISMA 2020 protocol, which ensures transparency in the selection, evaluation, and synthesis processes. Reliability is strengthened through MMAT, which assesses cross-method quality, and NVivo 14 thematic analysis, which identifies recurring patterns. However, limitations include a focus on publications from 2015 to 2025, which may exclude relevant studies; a predominance of East Asian research, limiting generalization; and heterogeneity in experimental design, dosage, and fertilizer form, complicating quantitative generalization.

This study highlights several important gaps: (1) limited long-term research (>5 seasons) on the accumulation and effects of liquid silica residues; (2) a lack of studies on the interaction of silica with soil microbiomes, despite evidence that it increases microbial activity; (3) a paucity of research across tropical and subtropical rice varieties; and (4) weak cost-benefit analyses for farmer adoption. Future research should integrate long-term field experiments with ecosystem modelling to assess silica's contribution to global productivity and climate mitigation.

Overall, this review confirms that the application of liquid silica enhances rice productivity, increases stem resistance to lodging, and promotes soil fertility sustainability. These findings are consistent with previous literature and add a new perspective on silica as a detoxification and carbon sequestration agent. Theoretically, it expands our understanding of plant physiology and soil fertility; practically, it provides a basis for the adoption of silica fertiliser technology; and in terms of policy, it supports food security and the health of rice field ecosystems. However, methodological limitations and variations in results underscore the need for further extensive, in-depth, and long-term research.

CONCLUSIONS AND SUGGESTION

The application of liquid silica in rice cultivation has been proven to increase yields by up to 58%, strengthen stem resistance to lodging through tissue strengthening, and improve rice field soil fertility by increasing pH, cation exchange capacity, microbial activity, and heavy metal immobilisation. Variations in results are influenced by factors such as dosage, fertiliser, variety, and environment. Further research is needed to assess cost-effectiveness and interactions with soil microbes. Its limitations include the focus of the 2015–2025 publications, which may exclude relevant studies; the predominance of East Asian research, which limits generalisability; and the heterogeneity of experimental designs, doses and fertiliser types, which hinders quantitative generalization. Future research needs to integrate long-term field experiments with ecosystem modelling to assess the contribution of silica to global productivity and climate mitigation.

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