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Role of Silicon in Organic and Inorganic Nutrient Management for Improving Growth, Yield and Quality of Black Gram (*Vigna mungo* L.): A Review

Rohit Kumar[1], Narendar Jannu[2], Nilotpal Das[3], Ramesh Abhishek[4], Atin Kumar[5], Sharad Sachan[6], Jitendra Singh[7], Pankaj Kumar[8]

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ABSTRACT

Black gram [*Vigna mungo* (L.)] is an important pulse crop widely cultivated for its high protein content, nitrogen-fixing ability and contribution to soil fertility improvement. However, the productivity of black gram is often constrained by nutrient imbalance, poor soil fertility and increasing abiotic stresses such as drought and salinity. Silicon (Si), although not recognized as an essential plant nutrient, has gained considerable attention because of its beneficial role in enhancing plant growth, nutrient-use efficiency, stress tolerance and crop productivity. Therefore, integrated use of silicon with organic and inorganic nutrient sources has emerged as a promising strategy for improving growth, yield, grain quality and sustainability in pulse-based cropping systems. This review work was carried out at the Faculty of Agricultural Sciences, GLA University and the School of Agriculture, Uttaranchal University. A systematic cum integrative review of research work conducted in different parts of the world, particularly in India, was comprehended. The literature search was conducted during 2024-2025. About 180 review and research papers were screened from various databases including Google Scholar, Scopus, ResearchGate, ARCC Journals, Web of Science and other scientific repositories, out of which relevant published papers were critically analyzed and used for preparation of this review manuscript. The reviewed studies demonstrated that integrated application of silicon with organic and inorganic nutrient sources significantly improved growth parameters, yield attributes, nutrient uptake, grain quality and post-harvest soil health in black gram and related crops. Silicon application enhanced plant height, root and shoot growth, chlorophyll content, photosynthetic efficiency, nutrient absorption and stress tolerance under adverse environmental conditions. Improved yield performance was associated with better water-use efficiency, balanced nutrient availability and enhanced physiological activities. Silicon-mediated improvement in grain quality, including higher protein content and improved mineral composition, was also reported. Furthermore, integrated nutrient management practices involving silicon contributed to improved soil microbial activity, nutrient cycling, organic carbon accumulation and long-term soil fertility. The findings indicate that silicon-based integrated nutrient management can serve as an eco-friendly and sustainable approach for improving productivity, quality and resilience of black gram production systems.

Key words: Black gram, Integrated nutrient management, Nutrient-use efficiency, Organic manure, Silicon, Soil health, Sustainable agriculture.

Black gram (*Vigna mungo* L.) is considered a crucial pulse crop in most of the Asian countries because of its high protein level and its potential to enrich the soil. Nevertheless, it is frequently limited in its productivity due to poor nutrient control and growing environmental pressures, including drought, salinity and nutrient imbalance of the soils. Silicon also plays an important role in alleviating nutritional disorders by regulating nutrient uptake and maintaining nutrient homeostasis (Ali *et al*., 2020). In this respect, silicon (Si), which is not considered an essential plant nutrient traditionally, has received a lot of interest due to its versatile advantages in agricultural production. Recent studies have highlighted the important role of silicon (Si) in enhancing plant tolerance against various abiotic and biotic stresses, including drought, salinity, heavy metal toxicity, temperature extremes and pathogen attack. Silicon improves antioxidant defense systems, osmotic regulation, photosynthetic efficiency and nutrient-use efficiency, thereby supporting better plant growth and productivity under stressful environmental conditions. In recent years, silicon nanoparticles have gained considerable attention because of their higher reactivity, improved absorption efficiency and potential use in precision and sustainable agriculture. Furthermore, advances in molecular biology

[1]Faculty of Agricultural Sciences, GLA University, Mathura-281 406, Uttar Pradesh, India.
[2]Department of Agronomy, Agricultural College, PJTAU, Warangal-506 007, Telangana, India.
[3]School of Agriculture, Uttaranchal University, Dehradun-248 007, Uttarakhand, India.
[4]Department of Natural Resource Management, Faculty of Agricultural Sciences, SGT University, Gurugram-122 505, Haryana, India.
[5]School of Agriculture, Uttaranchal University, Dehradun-248 007, Uttarakhand, India.
[6]Department of Agricultural Economics and Extension, School of Agriculture, Lovely Professional University, Phagwara-144 411, Punjab, India.
[7]Department of Soil Science and Agricultural Chemistry, Veer Kunwar Singh College of Agriculture, Bihar Agriculture University, Dumraon, Sabour-802 119, Bihar, India.
[8]Department of Entomology, Sardar Vallabh Bhai Patel University of Agriculture and Technology, Meerut-250 110, Uttar Pradesh, India.

Corresponding Author: Atin Kumar, School of Agriculture, Uttaranchal University, Dehradun-248 007, Uttarakhand, India.
Email: atinchaudhary0019@gmail.com

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have improved understanding of silicon uptake and transport mechanisms through specific transporter genes involved in silicon absorption, translocation and accumulation in plants. Silicon-based nutrient management is increasingly recognized as an eco-friendly and sustainable approach for improving crop resilience, soil health and agricultural productivity while reducing environmental risks associated with excessive fertilizer use (Pandey *et al*., 2024; Yan *et al*., 2024; Haider *et al*., 2025; Xing *et al*., 2025; Swaminathan *et al*., 2023).

Role of silicon in growth and development of plants

Silicon (Si), the second most abundant element in the Earth's crust after oxygen, has gained considerable attention in modern agriculture because of its beneficial role in plant growth, development and stress management. Although silicon is not classified as an essential nutrient for most plant species, numerous studies have demonstrated its significant contribution to improving plant vigor, productivity and resilience under both normal and stress conditions. Due to these beneficial effects, silicon is often regarded as a "quasi-essential" or beneficial element for sustainable crop production.

Plants absorb silicon mainly in the form of monosilicic acid [$Si(OH)_4$] from the soil solution through specific silicon transporters present in root cells. After absorption, silicon is translocated through the xylem and deposited in different plant tissues, particularly in epidermal cells, cell walls, leaves, stems and roots as amorphous silica. This deposition strengthens plant structural integrity and improves tolerance against various environmental stresses (Gaur *et al*., 2020; Pandey *et al*., 2024).

One of the major functions of silicon in plants is the enhancement of vegetative growth and physiological efficiency. Silicon application improves plant height, root growth, leaf area, biomass accumulation and chlorophyll content, thereby enhancing photosynthetic activity and dry matter production. Improved root architecture under silicon supplementation enhances water and nutrient absorption, which ultimately supports better plant growth and yield performance. Silicon also improves nutrient-use efficiency by regulating the uptake, translocation and balance of essential nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, iron and manganese (Rea *et al*., 2022; Shanmugaiah *et al*., 2023).

Silicon plays a crucial role in mitigating abiotic stresses such as drought, salinity, heavy metal toxicity, nutrient imbalance, temperature extremes and ultraviolet radiation stress. Under drought conditions, silicon reduces transpiration losses by forming a silica-cuticle double layer beneath leaf epidermal cells, thereby improving water-use efficiency and maintaining plant water balance. Similarly, under salinity stress, silicon minimizes sodium toxicity and enhances ionic balance by regulating ion transport and antioxidant defense systems. Several studies have reported that silicon enhances the activities of antioxidant enzymes such as superoxide dismutase, catalase and peroxidase, which help in scavenging reactive oxygen species generated during stress conditions (Èermelj *et al*., 2021; Kovács *et al*., 2022; Ajaykumar *et al*., 2023). Studies published in *Legume Research* have also demonstrated that improved nutrient management and balanced crop nutrition enhance stress tolerance, antioxidant activity and physiological efficiency in pulse crops under adverse environmental conditions (Swaminathan *et al*., 2023).

Furthermore, silicon significantly contributes to plant defense against biotic stresses including diseases, insect pests and pathogen attack. Silicon deposition in plant tissues strengthens cell walls and acts as a physical barrier against pathogen penetration and insect feeding. In addition, silicon activates various biochemical and molecular defense responses, including production of phytoalexins, phenolic compounds and defense-related enzymes. This enhanced resistance reduces disease incidence and improves overall plant health and productivity (Majumdar and Prakash, 2020; Shanmugaiah *et al*., 2023). Recent advances in silicon research have highlighted the growing importance of silicon nanoparticles in sustainable agriculture. Silicon nanoparticles possess higher surface area, improved reactivity and greater absorption efficiency compared with conventional silicon sources. Their application has shown promising results in improving seed germination, nutrient uptake, stress tolerance and crop productivity under adverse environmental conditions (Mahawar *et al*., 2023; Yan *et al*., 2024). Similarly, modern molecular and physiological studies have improved understanding of silicon transport mechanisms in plants. Specific transporter genes responsible for silicon uptake and translocation have been identified in several crop species, providing new opportunities for improving silicon-use efficiency through breeding and biotechnology approaches (Pandey *et al*., 2024; Sharma *et al*., 2022).

Overall, silicon has emerged as an important component of sustainable crop management due to its multifunctional role in improving plant growth, physiological performance, stress tolerance, nutrient-use efficiency, crop quality and soil-plant interactions. Its integration with organic and inorganic nutrient management practices may provide an eco-friendly and economically viable strategy for enhancing agricultural productivity and resilience under changing climatic conditions (Fig 1).

Organic and inorganic nutrient sources

Modern agriculture relies on organic and inorganic sources of nutrition, which have their own benefits and drawbacks in promoting the growth of the plants, the health of the soil and sustainable production of crops. The effects of these amendments last long-term and include positively influencing the long-term soil fertility and resistance to abiotic stresses such as drought, salinity and heavy metal toxicity, as well as the long-term accretion of soil organic carbon and nutrient cycling (Lazcano *et al*., 2021; Bhunia *et al*., 2021; Brichi *et al*., 2023) (Table 1). Combined nutrient management, where both organic and inorganic sources come together, is getting increasing acknowledgement as a sustainable solution that builds on the short-term nutrient supply of inorganic fertilisers and the long-term soil health of organic amendments. It improves the effectiveness of nutrient utilization, agro-productivity and economic productivity, reducing environmental risk factors and controlling the microbial diversity and enzymatic activity in the soil (Ejigu *et al*., 2024; Gezahegn, 2021; Sabir *et al*., 2021; Xing *et al*., 2025; Oyetunji *et al*., 2022). Improvement in soil organic carbon also enhances the availability and cycling of macro- and micronutrients (Dhaliwal *et al*., 2024). Similar benefits of integrated nutrient management through organic and inorganic inputs have also been reported in black gram under Indian conditions Ramamoorthy and Ariraman, 2023).

Interaction of silicon with organic and inorganic nutrients

The interaction between silicon, organic amendments and inorganic fertilizers and their collective influence on nutrient cycling, soil health and nutrient-use efficiency is illustrated in Fig 2. Silicon is not viewed as a crucial component, but it is also widely accepted that this substance has a positive effect, especially in cases of deficiency of certain nutrients or environmental stresses. Silicon may be used together with inorganic fertilizers to enhance nutrient utilization, prevent the occurrence of nutrient imbalances and mitigate the adverse impact of excessive fertilizer use, *e.g*., acidifying the soil or causing toxicity in heavy metals (Pavlovic *et al*., 2021; Rea *et al*., 2022; Zhao *et al*., 2021). The effect of silicon in correcting nutrient imbalances is especially interesting in the case of phosphorus and in this aspect, silicon could improve phosphorus uptake during deficiency and decrease phosphorus accumulation during excess conditions, thereby enabling plants to adjust to changing phosphorus content in the soil (Hu *et al*., 2020). Balanced nutrient management is particularly important in black gram because synergistic interactions among essential nutrients improve nutrient uptake, physiological activity and productivity (Ramamoorthy and Ariraman, 2023).

Silicon application and its impact on growth parameters of black gram

The supplementation of silicon has been demonstrated to have a beneficial effect on the growth parameters of the leguminous crops, such as black gram, in terms of the increase in plant vigor, nutrient uptake and resistance to environmental stresses. These physiological alterations are characterized by major increases in the important growth variables like plant height, length of roots and shoots, area of leaves and total biomass accretion. During stress (drought or salinity), silicon can improve the efficiency of water use, as well as minimize water loss, which leads to water being used sustainably and yield losses minimized. Such synergistic outcomes lead to better, higher, healthier black gram plants with more potential to grow under a suboptimal environment and high yield and quality. The positive effect of silicon on growth parameters of black gram may be associated with improved cell wall strength, enhanced chlorophyll synthesis, better root development and improved nutrient uptake efficiency. Similar improvements in physiological traits, chlorophyll content, root nodulation and biochemical activity have also been reported in black gram following application of biological stimulants and integrated nutrient management (Ajaykumar *et al*., 2023). Several studies have reported greater improvement under drought and salinity stress than under normal conditions, indicating that silicon acts more effectively as a stress-mitigating element. However, the magnitude of response varies depending on soil properties, silicon source, method of application and environmental conditions (Table 2). Therefore, further field-based investigations are necessary to optimize silicon management practices for different

Fig 1: Conceptual diagram showing the role of silicon in improving growth, stress tolerance and yield of black gram.

Table 1: Comparative features of organic and inorganic nutrient sources.

Feature	Organic nutrient sources	Inorganic nutrient sources	Citations
Nutrient release	Slow, gradual (mineralization-dependent)	Rapid, immediately available	(Chatzistathis *et al.*, 2021; Liu *et al.*, 2024; Priya *et al.*, 2024; Bhunia *et al.*, 2021)
Soil health impact	Improves structure, organic matter and microbial life	May degrade soil quality with overuse	(Chatzistathis *et al.*, 2021; Liu *et al.*, 2024; Bhunia *et al.*, 2021; Xing *et al.*, 2025)
Environmental impact	Lower risk of pollution, supports biodiversity	Risk of leaching, pollution and GHG emissions	(Chatzistathis *et al.*, 2021; Ejigu *et al.*, 2024; Bungău *et al.*, 2021; Haider *et al.*, 2025)
Crop yield response	Sustains yield long-term, may lag short-term	Boosts yield quickly, but may decline over time	(Ejigu *et al.*, 2024; Gezahegn, 2021; Salam *et al.*, 2021)
Cost and availability	Often locally available, may be labor-intensive	Commercially available, cost varies	(Chatzistathis *et al.*, 2021; Ejigu *et al.*, 2024; Bhunia *et al.*, 2021)
Integration benefits	Enhances nutrient cycling, resilience	Complements organic for balanced nutrition	(Ejigu *et al.*, 2024; Gezahegn, 2021; Sabir *et al.*, 2021; Xing *et al.*, 2025; Oyetunji *et al.*, 2022)

Table 2: Effect of Silicon on growth parameters of black gram.

Growth parameter	Effect of silicon application	Citations
Plant height	Increases due to enhanced cell elongation and structural support	(Rea *et al.*, 2022)
Root and shoot length	Significantly improved, supporting better nutrient and water uptake	(Shanmugaiah *et al.*, 2023)
Leaf area	Expanded leaf area, leading to higher photosynthetic capacity	(Kovács *et al.*, 2022)
Biomass accumulation	Greater total dry matter due to improved nutrient use and stress tolerance	(Rea *et al.*, 2022)
Nutrient uptake	Enhanced absorption of N, K, Ca, S, Fe and Mn, supporting overall plant growth	(Shanmugaiah *et al.*, 2023)
Stress tolerance	Improved drought and salinity resistance, maintaining growth under adverse conditions	(Kovács *et al.*, 2022)
Disease and pest resistance	Strengthened cell walls and induced defense responses reduce susceptibility	(Rea *et al.*, 2022; Shanmugaiah *et al.*, 2023; Kovács *et al.*, 2022)

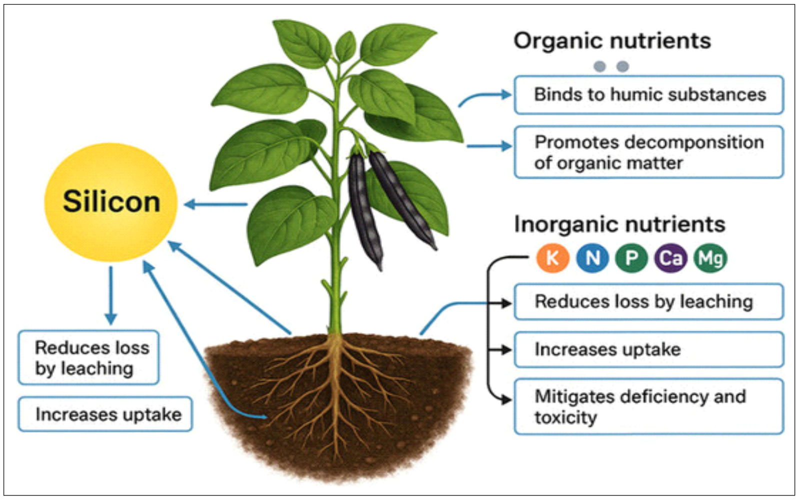

Fig 2: Diagrammatic representation of silicon action in controlling the dynamics of organic and inorganic nutrients in plants and the silicon-humic interaction and promotion of decomposition of organic material, silicon-leaching and silicon-root interactions, nutrient-use efficiency and silicon-sustainability of soil-plant systems by alleviating nutrient deficiencies and nutrient toxicities and promoting overall plant growth, nutrient-use efficiency and stability of soil-plant systems.

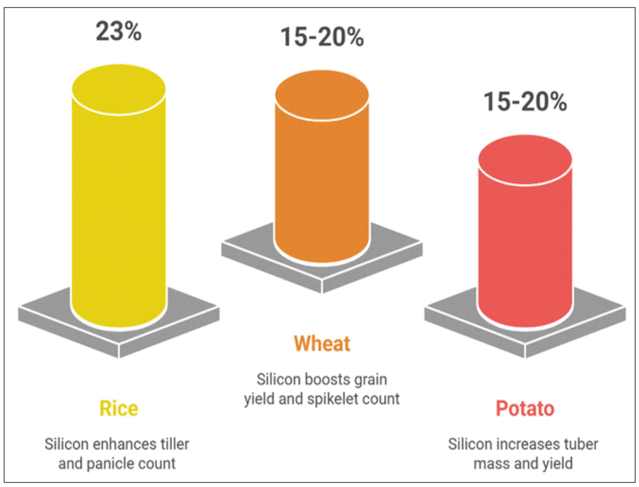

Fig 3: Relative representation of yield increase of key crops through silicon application, showing percentage production change of rice (increase of tiller and panicle number), wheat (increase of grain yield and spikelet number) and potato (increase of tuber mass and total yield), demonstrating the positive influence of silicon nutrition on yield-related characters of crops in various cropping systems.

agroecological regions (Rea *et al*., 2022; Shanmugaiah *et al*., 2023; Kovács *et al*., 2022) .

Silicon application substantially improves crop yield and yield attributes

The relative improvement in yield-related parameters of major crops following silicon application is presented in Fig 3. There is a strong and well-reported impact of silicon application on the crop yield and yield characteristics, particularly during abiotic and biotic stress conditions. The importance of silicon in enhancing drought tolerance is that it enhances the efficiency of water utilization in plants and decreases water loss potential, which allows crops to maintain a higher rate of productivity even when the water availability is limited. Yield enhancement through silicon application is primarily attributed to improved photosynthetic efficiency, enhanced water-use efficiency, balanced nutrient uptake and reduced oxidative damage under stress conditions. This may be attributed to the role of silicon in strengthening cell wall structure, regulating osmotic balance, enhancing antioxidant defense systems and improving nutrient absorption and translocation within plants (Rea *et al*., 2022; Shanmugaiah *et al*., 2023). Integrated application of silicon with organic and inorganic nutrient sources often produces better yield performance than the sole application of fertilizers because it improves both immediate nutrient availability and long-term soil fertility. Studies in black gram have consistently shown that integrated nutrient management enhances yield attributes, grain yield and profitability by improving nutrient availability and physiological efficiency. Similarly, studies published in Legume Research and other ARCC journals have reported that integrated nutrient management practices significantly improve crop productivity, nutrient-use efficiency and stress tolerance in pulse-based cropping systems through improved soil health and balanced nutrient availability (Swaminathan *et al*., 2023; Gezahegn, 2021; Salam *et al*., 2021). These findings indicate that silicon-based integrated nutrient management can contribute significantly to sustainable pulse production under changing climatic conditions.

Silicon application improves the quality parameters of crops in different species

Silicon use has turned out to be an effective aid towards enhancing the quality aspect of crops, which affects both the nutritional and postharvest qualities of crops. Silicon not only enhances the yield but also the quality of grain in cereals and legumes by enhancing protein and oil content, mineral composition and enhancing better grain filling, particularly in stressful situations (Rea *et al.*, 2022; Tayade *et al.*, 2022) (Fig 4). The beneficial impact of silicon in reducing heavy metal toxicity is especially crucial when it comes to food safety since the nutritional value and safety of food crops can be enhanced by the reduction of the toxic metals in edible parts of plants due to the presence of silicon (Rachappanavar *et al.*, 2024). The implementation of silicon in crop management not only increases the yield but also dramatically enhances the quality of agricultural products, which makes it an important measure to address the needs of consumers and provide food security despite environmental factors. Several studies have reported that silicon-mediated improvement in grain quality is associated with enhanced nutrient translocation, improved metabolic activity and better stress tolerance during reproductive stages. Increased protein accumulation and improved mineral composition observed under silicon application indicate its potential role in improving nutritional quality and food security. Similarly, studies published in Legume Research and other ARCC Journals have demonstrated that integrated nutrient management and balanced nutrient supply significantly enhance protein synthesis, seed quality, nutrient uptake and overall physiological efficiency in pulse crops (Swaminathan *et al.*, 2023; Gezahegn, 2021; Salam *et al.*, 2021). However, most available studies have mainly focused on cereals, whereas information regarding silicon-induced quality improvement in legumes such as black gram remains limited. Therefore, further crop-specific investigations are needed to better understand the role of silicon in improving grain quality and nutritional characteristics in pulse-based production systems (Rea *et al.*, 2022; Rachappanavar *et al.*, 2024; Tayade *et al.*, 2022). Balanced nutrient management has also been reported to improve grain quality, nutrient uptake and economic returns in black gram (Ramamoorthy and Ariraman, 2023).

Post-harvest soil health and status of soils

Reintroducing crop residues to soil is often discussed as one of the primary methods of soil health maintenance or improvement because of raising its organic carbon levels, improving aggregate stability, improving the capacity to exchange cations and augmenting the supply of necessary nutrients like nitrogen, phosphorus and potassium (Fu *et al.*, 2021; Sarkar *et al.*, 2024) (Table 3). Combinations of organic nutrient additives, such as compost or biochar, with mineral nutrient additives have been demonstrated to increase nutrient use efficiency, soil pH and positive microbial communities, which contribute to a better use of nutrients and lower environmental losses. Similarly, integrated nutrient management practices involving organic amendments and balanced fertilizer application have been reported to improve soil biological activity, nutrient availability and long-term soil fertility in pulse-based cropping systems. Integrated use of silicon with organic and inorganic nutrient sources may improve post-harvest soil health by enhancing soil microbial activity, organic carbon accumulation, nutrient cycling and aggregate stability. Organic amendments combined with silicon can also reduce nutrient losses and improve soil resilience against

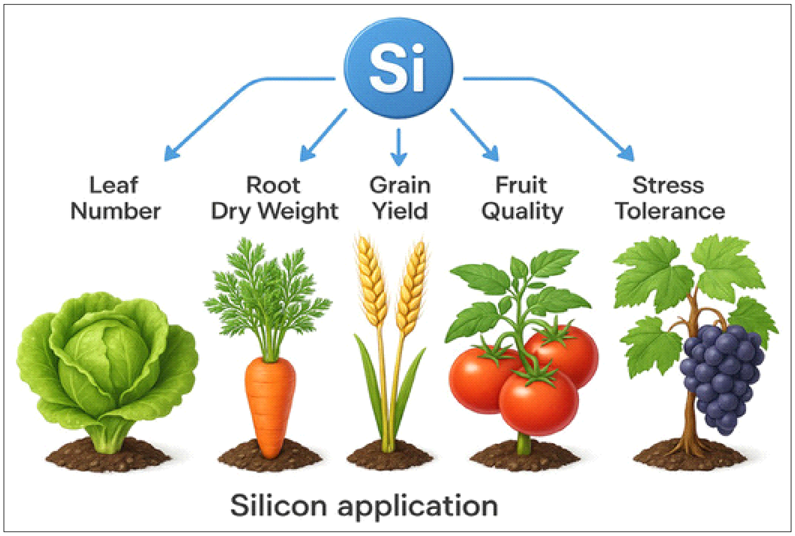

Fig 4: Conceptual representation of the outcomes of silicon (Si) use on important growth and productivity indicators of plants, such as an increased number of leaves, increased root dry mass, improvement in the grain yield, better fruit quality and increased resistance to both biotic and abiotic stresses in various crop species.

Table 3: Key impacts of post-harvest practices on soil health and nutrient status.

Practice/factor	Effect on soil health and nutrient status	Citations
Crop residue retention	Increases organic carbon, nutrient availability and aggregate stability	(Fu *et al.*, 2021; Sarkar *et al.*, 2024)
Cover cropping	Enhances soil structure, microbial activity and nutrient cycling	(Koudahe *et al.*, 2022; Scavo *et al.*, 2022)
Conservation tillage/no-till	Reduces erosion, maintains organic matter and improves water retention	(Xing *et al.*, 2025; Montgomery *et al.*, 2022; Sarkar *et al.*, 2024)
Organic amendments (compost, biochar)	Boosts nutrient retention, soil fertility and microbial diversity	(Alkharabsheh *et al.*, 2021; Oyetunji *et al.*, 2022)
Excessive residue removal	Depletes organic matter, reduces nutrients and increases erosion risk	(Battaglia *et al.*, 2020; Sarkar *et al.*, 2024)
Integrated nutrient management	Improves nutrient use efficiency, maintains pH, supports soil biota	(Alkharabsheh *et al.*, 2021; Oyetunji *et al.*, 2022)
Regenerative/organic practices	Higher soil health scores, increased micronutrient and phytochemical content	(Montgomery and Biklé, 2021; Montgomery *et al.*, 2022)

degradation. Similar findings were also reported in pulse and legume-based production systems, where integrated nutrient management improved soil physicochemical properties, microbial activity and sustainable crop productivity (Swaminathan *et al*., 2023; Gezahegn, 2021; Ejigu *et al*., 2024). However, limited long-term field studies are available regarding the residual effects of silicon application on soil physicochemical and biological properties in pulse-based cropping systems. Therefore, future research should focus on long-term sustainability assessment under diverse agro-climatic conditions (Alkharabsheh *et al*., 2021; Oyetunji *et al*., 2022).

FUTURE PERSPECTIVES

Due to the growing body of research, silicon is emerging as an important constituent to enhance crop productivity and resilience, although it is not deemed to be essential to all plants. Another direction is the use of silicon-solubilizing microorganisms as bioinoculants, which allows agrowaste and soil minerals to mobilize silicon, eliminating the use of chemical fertilizers and upholding the concept of the circular economy (Sharma *et al*., 2022). Nevertheless, future studies should adopt various gaps in the knowledge base, including the specifics of silicon uptake and transportation in black gram, the relations of silicon and other nutrients in different soil and environment conditions and the potential outcomes of recurrent silicon application on the state of the soil and privation of crops (Rea *et al*., 2022; Pavlovic *et al*., 2021; Kovács *et al*., 2022). Crop-specific studies are also required since the majority of silicon studies have been carried out on cereals and few studies have been done on legumes such as black gram. Field tests, molecular research and enhanced phenotyping will be necessary to maximize silicon management plans adapted to the physiology and local agroecosystems of black gram. Also, the economic and environmental sustainability of various silicon sources, balancing the cost, availability and ecological impact, would become a paramount consideration towards wide adoption. Overall, the future of silicon use in black gram production is in integrated, science-based solutions that merge organic and inorganic sources, embrace emerging technology and meet productivity and sustainability objectives, which will eventually result in enhanced black gram production systems that are resilient, high-quality and profitable (Rea *et al*., 2022; Pavlovic *et al*., 2021; Mahawar *et al*., 2023; Tayade *et al*., 2022; Kovács *et al*., 2022; Sharma *et al*., 2022).

CONCLUSION

The research on silicon under organic and inorganic sources of nutrients on growth, yield and quality of black gram (*Vigna mungo* L.) is a clear indication of the usefulness of silicon in enhancing crop growth, yield and soil fertility. Silicon addition to the mixture of balanced sources of nutrients, organic and inorganic, led to improvement of vegetative growth, nodulation and physiological efficiency, which contributed to the increased yield and high-quality grains. Silicon enhanced nutrient acquisition, enhanced the plant cell walls and made the plant more resistant to both biotic and abiotic stress and this alone led to the overall healthiness of the plant. Furthermore, the use of silicon together with organic manures like farmyard manure or vermicompost and inorganic fertilizers offered a sustained and balanced supply of nutrients and better soil structure and microbial activities. This comprehensive nutrient management method has resulted in increased productivity and, at the same time, ensured soil health and sustainability in pulse-based cropping systems. It can therefore be concluded that judicious use of silicon together with organic and inorganic sources of nutrients is a good approach towards maximizing growth, yield and quality of black gram as well as guaranteeing long-term soil fertility and sustainable agricultural production.

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Disclaimers

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Conflict of interest

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