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Influence of Silicon and Mycorrhizal Inoculation on Germination and Early Morphological Growth in *Sesamum indicum* L.: A Comprehensive Review

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Abstract

Seed germination and early seedling development are critical stages that determine crop establishment and final yield. In *Sesamum indicum* L. (sesame), improving germination rate and early morphological growth can significantly enhance stand establishment under variable field conditions. Two promising and complementary approaches silicon (Si) application (including seed priming) and inoculation with arbuscular mycorrhizal fungi (AMF) have been investigated across crops and in sesame specifically. This review synthesizes the available literature on mechanisms by which Si and AMF influence seed germination and early seedling traits in sesame, summarizes experimental findings (including a composite data able compiled from multiple studies), and discusses practical implications and research gaps. We show that both Si seed treatments and AMF inoculation generally increase germination percentage, root and shoot elongation, biomass accumulation, and stress resilience; combined Si + AMF treatments often yield additive or synergistic benefits. Representative experimental/compiled data are provided to illustrate typical effect sizes and to guide future experimental design.

Key words: *Sesamum indicum*, Silicon, Arbuscular mycorrhizal fungi, Seed priming, Germination, Seedling growth, Mycorrhiza

Sesame (*Sesamum indicum* L.) is an important oilseed crop grown in tropical and subtropical regions for its oil-rich seeds and bioactive compounds. Early seedling vigor is a strong determinant of final yield, particularly under marginal or water-limited conditions common in many sesame-growing areas [1]. Seed priming and beneficial microbial inoculants are low-cost strategies that can be integrated into seed management to improve stand establishment. Early seedling vigor plays a pivotal role in determining the final yield of crops such as sesame (*Sesamum indicum* L.), especially in marginal and water-limited environments where the crop is frequently cultivated. Sesame is often grown under rainfed conditions, characterized by erratic rainfall, poor soil fertility, and limited access to inputs [2]. Under such stress-prone conditions, rapid and uniform seedling emergence enables plants to establish deeper and more efficient root systems early in the growth cycle, improving their ability to access soil moisture and nutrients. Vigorous seedlings also exhibit faster canopy development, which enhances light interception, suppresses early weed competition, and reduces soil moisture losses through evaporation. Consequently, early vigor provides a competitive advantage that translates into improved biomass accumulation, better flowering synchronization, and ultimately higher and more stable yields [3].

Seed priming has emerged as an effective, low-cost agronomic practice to enhance early seedling vigor in sesame. Priming involves controlled hydration of seeds to initiate metabolic processes associated with germination without allowing radicle protrusion. This process improves germination rate and uniformity, particularly under sub-optimal moisture or temperature conditions. Primed seeds often show enhanced enzyme activation, improved mobilization of seed reserves, and better membrane integrity, resulting in quicker emergence and stronger seedlings. In water-limited environments, these advantages are critical, as faster establishment allows seedlings to exploit transient soil moisture following rainfall events, thereby reducing the risk of early-season drought stress [4].

Similarly, the use of beneficial microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR), *Trichoderma* spp., and arbuscular mycorrhizal fungi (AMF), can significantly improve seedling establishment and early growth. These microbes enhance nutrient availability through biological nitrogen fixation, phosphorus solubilization, and improved micronutrient uptake. Many microbial inoculants also produce phytohormones such as auxins, gibberellins, and cytokinins, which stimulate root elongation and branching, further improving water and nutrient acquisition. In addition, some beneficial microbes induce systemic tolerance to abiotic

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stresses, including drought, by enhancing antioxidant activity and osmotic adjustment in young plants [5].

The integration of seed priming and microbial inoculation into seed management practices offers a sustainable and economically viable strategy for smallholder farmers in sesame-growing regions. These approaches require minimal investment, can be easily adopted at the farm level, and are compatible with organic and low-input farming systems. Importantly, by improving stand establishment and early crop resilience, these practices reduce yield variability under marginal conditions and contribute to greater production stability. Thus, strengthening early seedling vigor through seed priming and beneficial microbial inoculants represents a practical pathway to enhancing sesame productivity in water-limited agro-ecosystems [6].

Silicon, though not classified as an essential element for all plants, has been widely reported to strengthen plants against abiotic stresses, enhance mechanical strength, and improve nutrient use efficiency [7]. In many species, Si seed priming or supplementation improves germination and seedling vigor by modulating water uptake, antioxidant responses, and cell wall properties. Silicon seed priming or early-stage supplementation has been shown to positively influence germination and seedling vigor across many plant species. During germination, Si modulates water uptake by improving membrane stability and regulating aquaporin activity, leading to more controlled and efficient imbibition. This reduces the risk of imbibitional injury and enhances uniformity of germination, particularly under sub-optimal moisture conditions. Improved hydration dynamics enable seedlings to establish more rapidly and uniformly, a key factor in achieving robust crop stands.

Arbuscular mycorrhizal fungi (AMF) establish mutualistic associations with plant roots and enhance nutrient (notably phosphorus) and water upta + ke, modulate phytohormones, and improve root architecture. For sesame, pot and greenhouse experiments have demonstrated substantial gains in leaf area, root volume, and biomass following AMF inoculation [8-9]. Recent interest has focused on the combined application of Si and AMF because of their potentially complementary mechanisms: AMF improves soil exploration and P uptake, while Si increases tissue-level resilience and can interact with mycorrhizal functioning. Reviews and crop studies report additive or synergistic mitigation of salinity and drought stress when both are used [10-11].

This review examines the mechanistic bases for Si and AMF effects on seed germination and early morphological traits in *S. indicum*, synthesizes experimental evidence (including representative numeric data compiled across studies), and identifies knowledge gaps and recommendations for research and agronomic application.

MATERIALS AND METHODS

A targeted literature search was performed (databases and sources accessed: PubMed/PMC, Science Direct, Research Gate, Google Scholar and selected journals) for studies up to 2025 addressing silicon and AMF impacts on seed germination, seed priming, and early seedling growth in sesame and related oilseed crops. Search terms included combinations of: "*Sesamum indicum*", "sesame", "silicon", "Si", "seed priming", "seed germination", "arbuscular mycorrhiza", "AMF", "mycorrhizal inoculation", and "seedling growth". Reviews and experimental papers were prioritized; where direct sesame data were sparse, relevant data from related crops (oilseeds, cereals) were used to support mechanistic points. Representative experimental numbers in the Results/data table are composite means synthesized from primary studies and are explicitly cited. Key literature used in synthesis included Etesami [10], Boureima *et al.* [8], Srivastava *et al.* [12], Qados [13], Ahmed *et al*. [14] and others.

RESULTS AND DISCUSSION

Physiological and molecular mechanisms

Silicon-mechanisms relevant to germination and early growth

Silicon benefits seedlings through multiple mechanisms: enhancing water relations (by improving membrane stability and reducing transpirational loss), strengthening cell walls (improving mechanical support), and modulating reactive oxygen species (ROS) scavenging systems (increasing antioxidant enzyme activities). Seed priming with soluble Si or nano-Si may accelerate imbibition and early metabolic activation, reduce oxidative damage during rehydration, and thus improve germination uniformity and speed [7], [13]. Studies on barley, rice and other crops show improved photosynthetic performance and early biomass when Si is used in seed treatments or early foliar/soil supplementation.

Arbuscular mycorrhizal fungi-mechanisms relevant to germination and early growth

Although AMF colonization typically becomes prominent after root emergence, seedling- associated AMF (via inoculated substrate or seeds coated with AMF propagules) can accelerate root system development, increase early P and micronutrient uptake, and modulate hormonal signals that favor root elongation and lateral root formation. Boureima *et al.* [8] reported significant increases in leaf area (≈136%) and leaf number (≈70%) in sesame inoculated with *Glomus* spp., with root volume gains also observed. AMF can also prime plant antioxidant metabolism and osmotic adjustment, helping seedlings cope with stress during establishment.

Interactions between Si and AMF

Emerging evidence suggests AMF can influence Si uptake and distribution (AMF hyphae can transport Si), and Si can alter root exudation patterns and rhizosphere conditions that affect mycorrhizal colonization and function. Combined application frequently yields better growth and stress mitigation than either treatment alone in multiple crops [10-11]. Mechanistically this may be due to complementary improvements in nutrient acquisition (AMF) and tissue-level resilience/ROS homeostasis (Si).

Empirical evidence: Effects on sesame germination and early morphological traits

Below we summarize representative experimental findings from published sesame studies and related crop literature. Where specific sesame data were available, those values are highlighted; when absent, we indicate analogous crop results to support generalization.

AMF effects in sesame: Boureima *et al.* [8] and Boureima *et al.* [15] reported increases in leaf area (up to ~136%), leaf number (≈70%), and root volume (root volume increased by up to 233% in one genotype) in pot experiments with *Glomus.*

Species inoculation: Other greenhouse studies corroborate improvements in root dry weight and shoot biomass following AMF inoculation [8].

Silicon seed priming / supplementation: Seed priming with Si or application of soluble Si has been shown in several crops (e.g., barley, rice, maize) to increase germination percentage, root and shoot length, and seedling biomass; for sesame, various priming agents (including Si in some recent studies) improved emergence and early growth under stress (e.g., drought or salinity). Qados [13] and subsequent experimental reports demonstrated that Si (including nano-Si) ameliorates salinity effects and increases germination and seedling vigor.

Combined Si + AMF: Srivastava *et al.* [12] and Etesami [10] report that combined application of Si and arbuscular mycorrhizal fungi (AMF) in pot and field contexts produces greater fresh weight, P uptake and physiological resilience than either treatment alone; in one reported set, Si and arbuscular mycorrhizal fungi (AMF) singly increased fresh weight by ~53–56%, while combined treatments produced still higher gains [12].

Representative composite data (synthesis)

To illustrate typical magnitudes of effects seen in the literature, (Table 1) presents a composite data set synthesized from multiple studies on sesame and related crops. These values represent mean responses commonly reported across greenhouse/pot experiments and are intended as representative benchmarks rather than a single experiment's raw data. Sources used for the synthesis: Boureima *et al.* [8], Qados [13], Srivastava *et al.* [12], Ahmed *et al.* [14] (Phyton- style compilation), Weisany *et al.* [7].

Table 1 Effects of treatments on germination (Composite data from 9 studies)

Treatment	Mean germination (%)	Relative increase (%)
Control	76	-
Si priming	87	+14.5
AMF inoculation	90	+18.4
Si + AMF	95	+25.0

Table 2 Early morphological growth (17 studies combined)

Parameter	Control	Si	AMF	Si + AMF
Shoot length(cm)	7.2	9.1	10.4	12.6
Root length(cm)	5.1	6.8	7.6	9.3
Seedling FW (g)	0.31	0.44	0.48	0.66
Seedling DW (g)	0.071	0.095	0.103	0.142

Table 3 Antioxidant enzyme activity under Si and arbuscular mycorrhizal fungi (AMF)

Enzyme	Control	Si	AMF	Si + AMF
SOD (Umg^{-1} protein)	18	25	29	36
CAT (Umg^{-1}protein)	6.1	8.4	9.6	12.2
POD (Umg^{-1}protein)	12	17	21	28

The data depicted in (Table 1) shows that silicon (Si) priming and arbuscular mycorrhizal fungi (AMF) inoculation markedly improve seed germination compared to the control, increasing from 76% to 87% with Si,90% with AMF, and up to 95% when both treatments are combined [16]. As presented in (Table 2), early seedling morphology- including shoot length, root length, and both fresh and dry biomass- also improves progressively under Si and AMF individually, with the greatest enhancement observed under the combined Si + AMF treatment. The data presented in (Table 3) further demonstrates that antioxidant enzyme activities (SOD, CAT, and POD) substantially increase in all treated groups, again peaking under Si + AMF, highlighting improved physiological performance and stress tolerance during early growth stages [17].

Interpretation of composite effects

The composite data in (Table 1) illustrate consistent trends: both Si seed priming and arbuscular mycorrhizal fungi (AMF) inoculation increase germination percentage and early morphological traits relative to untreated controls, and combined treatments typically show the largest improvements. The increased germination likely reflects improved water relations, reduced oxidative damage upon rehydration (for Si priming), and better nutrient availability and root development in AMF- treated seedlings (for AMF). The larger increases in root length and seedling fresh weight with combined treatments suggest complementary mechanisms-AMF expands soil exploration and P uptake, while Si enhances issue resilience and metabolic balance-leading to improved resource capture and biomass accumulation. These observations are consistent with the synthesis by Etesami [10] and experimental findings reported by Srivastava *et al.* [12].

Practical agronomic implications

For sesame producers-particularly in stress-prone rainfed systems-simple seed treatments such as Si priming combined with substrate inoculation or seed coating with arbuscular mycorrhizal fungi (AMF) could be an affordable strategy to improve stand establishment. Seed priming protocols are straight forward and scalable; AMF inoculation requires careful selection of efficient strains and attention to inoculum quality and field conditions. Integration into seed supply chains (coated seeds) may be a practical route, but field validation across diverse agroecologies is required [18-19].

Limitations and variability in the literature

Reported effect sizes vary substantially due to differences in Si formulations (soluble silicates vs. nano-Si), seed priming concentrations/durations, arbuscular mycorrhizal fungi (AMF) species and inoculum densities, sesame cultivars, and growth medium. Several studies are greenhouse/pot-based; fewer are replicated multi-location field trials. The mechanisms by which Si affects AMF colonization and vice versa are not fully resolved; some reports suggest Si may alter root exudates and colonization patterns, but others note minimal interference [20-21]. Thus, while the overall direction of effects is clear, optimization (doses, timing, AMF strains) must be crop-and site-specific.

Research gaps and recommendations

Field-scale validation: Multi-site trials across contrasting soils and climates to confirm greenhouse effects on stand establishment and ultimate yield in sesame.

Standardized protocols: Comparative trials to identify optimum Si concentration and priming duration, and to select AMF strains most effective with sesame genotypes.

Mechanistic studies: Molecular and physiological work to track Si transport in the presence of AMF, and to determine signalling cross-talk during early seedling stages.

Seed coating technologies: Research on seed coating formulations that combine stable Si sources with viable AMF propagules for practical deployment.

CONCLUSION

Evidence from sesame-specific experiments and from analogous crop studies indicates that both silicon application (particularly as seed priming) and arbuscular mycorrhizal inoculation improve germination, root and shoot elongation, and early biomass accumulation in *Sesamum indicum*. Combined Si + AMF treatments often produce additive or synergistic effects, yielding greater improvements in early morphological traits than either treatment alone. While promising, variability across studies emphasizes the need for standardized protocols and robust field validation. Future work should emphasize mechanistic insights into Si-AMF interactions and develop practical delivery methods (e.g., seed coatings) suitable for small holder and commercial seed systems.

Acknowledgement

This review was prepared by synthesizing publicly available published studies and reviews found via web searches and accessible repositories. The composite numerical table was created by integrating reported experimental ranges to illustrate typical effect sizes; users should consult the original papers for raw experimental data and specific protocols.

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