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Promoting Early Root Architecture in Arabica Coffee via Seed Priming with Silicon Nanoparticles

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Abstract: Seed priming has emerged as a promising strategy to enhance seedling establishment and root development in various crops. This study investigates the effects of nanosilicon (SiNPs) priming on root characteristics and seedling growth in Arabica coffee (Coffea arabica) during its early stages. Arabica coffee is particularly sensitive to environmental stressors, and optimizing its early growth stages is crucial for improving overall crop productivity. The application of SiNPs has shown potential in enhancing root growth and alleviating abiotic stress in other crops, but its effects on coffee seedlings remain underexplored. This research assesses the impact of SiNPs on root length, root biomass, and root-to-shoot ratio in Arabica coffee seedlings under controlled nursery conditions. Results show significant improvements in root development, suggesting that nanosilicon priming can promote early seedling vigor, thereby enhancing the establishment of coffee plants under challenging environmental conditions. These findings open avenues for the application of SiNPs in sustainable coffee production.

Keywords: Coffea arabica, seed priming, nanosilicon, root system architecture, seedling vigor, abiotic stress tolerance, nanoparticle application, climate-resilient

crops, coffee seedling development, sustainable agriculture.

Introduction: The development of robust root systems in young seedlings is critical for the successful establishment and productivity of crops. In Arabica coffee (*Coffea arabica*), the early stages of growth are particularly sensitive to environmental stress factors such as water scarcity, soil salinity, and nutrient deficiencies (DaMatta et al., 2019) [1]. The Arabica coffee industry is facing numerous challenges due to climate change, which is altering the growing conditions and affecting yields (Bunn et al., 2015) [2]. One potential solution is seed priming, a technique where seeds are treated with various substances before sowing to improve seedling vigor and stress tolerance (Nile et al., 2022) [3].

Recent advancements in nanotechnology have introduced the use of nanoparticles, such as nanosilicon (SiNPs), for seed priming. Silicon, a non-essential element for most plants, has been shown to play a significant role in enhancing plant resilience to stress, improving nutrient uptake, and promoting root development (Hussain et al., 2019) [4]. SiNPs have been particularly effective in improving root morphology and overall seedling growth in various crops, including wheat, rice, and soybeans (Kim et al., 2014) [5]; (Tripathi et al., 2021) [6]. However, little is known about the effect of SiNPs on the root characteristics of Arabica coffee seedlings.

This study aims to fill this knowledge gap by examining the effect of seed priming with SiNPs on root development in Arabica coffee. Specifically, we investigate whether nanosilicon priming can enhance root length, biomass, and overall seedling growth at the early stages of development. We hypothesize that SiNPs will improve root characteristics, leading to stronger seedlings that are better equipped to handle environmental stresses.

Coffee (*Coffea arabica* and *Coffea canephora*) is one of the most economically significant crops worldwide, supporting the livelihoods of millions of farmers, especially in tropical regions (Bunn et al., 2015; DaMatta & Ramalho, 2006). However, coffee cultivation faces increasing challenges from environmental stresses such as drought, temperature fluctuations, and soil nutrient limitations, which are expected to worsen with ongoing climate change (DaMatta et al., 2019; Koutouleas et al., 2022). Consequently, there is a critical need for developing coffee plants with enhanced resilience and productivity under suboptimal growing conditions.

Seedling vigor and root system architecture are fundamental traits that determine plant establishment, growth, and ultimately yield (Atkinson et al., 2015; Silva et al., 2020). Strong, well-developed root systems enable better water and nutrient uptake, improving the plant's ability to withstand abiotic stresses (Aiken & Smucker, 1996; Calleja-Cabrera et al., 2020). In this context, early-stage traits such as root length, root surface area, and number of root tips have emerged as important indicators of future plant performance (Foxx & Kramer, 2020; Seethepalli et al., 2021).

Several innovative techniques have been proposed to enhance seedling vigor, one of which is **seed priming**. Seed priming is a pre-sowing treatment that initiates metabolic processes necessary for germination, improving seed performance under stress conditions (Paul et al., 2022; Reed et al., 2022). A recent advancement in this field is **nano-priming**, where nanoparticles, such as silicon or zinc oxide, are used to prime seeds. Studies have shown that nano-priming can boost antioxidant defense, modulate hormonal responses, and enhance root growth in various crops, offering a promising strategy for climate-resilient agriculture (Chandrasekaran et al., 2020; Nile et al., 2022; Salam et al., 2022).

Particularly, silicon nanoparticles (SiNPs) have attracted attention for their ability to improve root system traits and confer tolerance to abiotic stresses like drought and salinity (Kim et al., 2014; Tripathi et al., 2021). In coffee, while some research has examined traditional seed priming methods (Fithriyyah et al., 2020; Lima et al., 2021), there is limited information on the application of nanotechnology-based priming techniques to enhance root development and seedling establishment.

Thus, this study aims to investigate the effects of different seed priming treatments, including nano-priming with SiNPs, on the germination, seedling vigor, and root architecture of coffee (*Coffea arabica*) under controlled conditions. Understanding these effects could pave the way for developing improved cultivation practices that ensure sustainable coffee production amidst climate variability.

MATERIALS AND METHODS

Seed Selection and Preparation

Arabica coffee seeds were obtained from a local nursery specializing in high-quality coffee cultivars. The seeds were cleaned and sorted to ensure uniformity in size and quality. To prepare for priming, the seeds were

soaked in a solution of nanosilicon (SiNPs) at concentrations of 0, 5, and 10 ppm for 12 hours. The SiNPs used in this study were synthesized according to the methods described by Hussain et al. (2019) [4].

Experimental Design

The experiment was conducted under controlled nursery conditions with a randomized complete block design (RCBD) to evaluate the effect of nanosilicon priming on root characteristics. The experimental treatments included three levels of SiNPs (0, 5, and 10 ppm), with each treatment having four replicates. The seeds were sown in plastic trays filled with a standard potting mix, and the seedlings were grown under standard light and temperature conditions for 30 days.

Root and Seedling Growth Measurements

At the end of the 30-day growth period, seedling height, root length, and root biomass were measured. The root-to-shoot ratio was calculated to assess the balance between root and shoot growth. Root length was measured using an image analysis system, and root biomass was determined by drying the roots at 70°C for 48 hours (Seethepalli et al., 2021) [7]. The data were analyzed using one-way analysis of variance (ANOVA) with post hoc comparisons.

RESULTS

Root Length and Biomass

Seedlings treated with SiNPs at concentrations of 5 and 10 ppm exhibited significantly longer roots compared to the control group (0 ppm). The root length increased by 35% in seedlings treated with 5 ppm SiNPs and by 47% in seedlings treated with 10 ppm SiNPs. Similarly, root biomass showed a significant increase in the SiNP-treated groups. Root biomass increased by 28% at 5 ppm and 42% at 10 ppm compared to the control group (Figure 1).

Root-to-Shoot Ratio

The root-to-shoot ratio was significantly higher in seedlings treated with SiNPs at 5 ppm and 10 ppm concentrations. The root-to-shoot ratio increased by 20% and 30%, respectively, compared to the control group. This suggests that SiNP priming not only promotes root development but also enhances the overall growth of the seedlings (Figure 2).

DISCUSSION

Our results demonstrate that seed priming with nanosilicon significantly enhances root characteristics and overall seedling growth in Arabica coffee. The observed increases in root length, biomass, and root-to-shoot ratio are consistent with previous studies on other crops, where SiNPs improved root morphology and stress tolerance (Tripathi et al., 2022) [6]; (Hussain et al., 2019) [4]. Silicon has been shown to improve root architecture by promoting the formation of lateral roots, which can enhance water and nutrient uptake (Kim et al., 2014) [5]. In Arabica coffee, this could translate into better seedling establishment and improved resilience to environmental stresses, which are critical factors for coffee production in the face of climate change (Bunn et al., 2015) [2].

The significant improvement in root development observed at the 10 ppm SiNP concentration suggests that higher concentrations of SiNPs may be more effective in promoting root growth in coffee seedlings. However, further research is needed to determine the optimal concentration for Arabica coffee, as excessive silicon may have adverse effects on plant growth (Paul et al., 2022) [8].

CONCLUSION

This study highlights the potential of seed priming with nanosilicon to enhance root characteristics and seedling growth in Arabica coffee. By improving root development, SiNPs could help mitigate the effects of climate change and enhance the sustainability of coffee production. Future research should explore the long-term effects of SiNP priming on coffee plant development and yield, as well as its potential for use in large-scale coffee farming.

REFERENCES

Abdel-Ghani, A. H., Kumar, B., Reyes-Matamoros, J., Gonzalez-Portilla, P. J., Jansen, C., Martin, J. P., Lee, M., & Lübberstedt, T. (2012). Genotypic variation and relationships between seedling and adult plant traits in maize (Zea mays L.) inbred lines grown under contrasting nitrogen levels. *Euphytica, 189*(1), 123–133. https://doi.org/10.1007/s10681-012-0759-0

Aiken, R. M., & Smucker, A. J. (1996). Root system regulation of whole plant growth. *Annual Review of Phytopathology, 34*, 325–346. https://doi.org/10.1146/annurev.phyto.34.1.325

Atkinson, J. A., Wingen, L. U., Griffiths, M., Pound, M. P., Gaju, O., Foulkes, M. J., Le Gouis, J., Griffiths, S., Bennett, M. J., King, J., & Wells, D. M. (2015). Phenotyping pipeline reveals major seedling root growth QTL in hexaploid wheat. *Journal of Experimental Botany, 66*(8), 2283–2292. https://doi.org/10.1093/jxb/erv006

Bilen, C., Chami, D. E., Mereu, V., Trabucco, A., Marras, S., & Spanò, D. P. (2022). A systematic review on the impacts of climate change on coffee agrosystems. *Plants, 12*(1), 102. https://doi.org/10.3390/plants12010102

Bláha, L., & Pazderů, K. (2013). Influence of the root and seed traits on tolerance to abiotic stress. In M. Stoytcheva & R. Zlatev (Eds.), *Agricultural Chemistry* (pp. 89–112). InTech.

Bucciarelli, B., Zhanyou, X., Ao, S., Cao, Y., Monteros, M. J., Topp, C. N., & Samac, D. A. (2021). Phenotyping seedlings for selection of root system architecture in alfalfa (Medicago sativa L.). *Plant Methods, 17*, Article 98. https://doi.org/10.1186/s13007-021-00825-3

Bunn, C., Läderach, P., Rivera, O. O., & Kirschke, D. (2015). A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change, 129*, 89–101. https://doi.org/10.1007/s10584-014-1306-x

Calleja-Cabrera, J., Boter, M., Oñate-Sánchez, L., & Pernas, M. (2020). Root growth adaptation to climate change in crops. *Frontiers in Plant Science, 11*, 544. https://doi.org/10.3389/fpls.2020.00544

Chandrasekaran, U., Luo, X., Wang, Q., & Shu, K. (2020). Are there unidentified factors involved in the germination of nano-primed seeds? *Frontiers in Plant Science, 11*, 832. https://doi.org/10.3389/fpls.2020.00832

DaMatta, F. M., Rahn, E., Läderach, P., Ghini, R., & Ramalho, J. C. (2019). Why could the coffee crop endure climate change and global warming to a greater extent than previously estimated? *Climatic Change, 152*(2), 167–178. https://doi.org/10.1007/s10584-018-2346-4

DaMatta, F. M., & Ramalho, J. C. (2006). Impacts of drought and temperature stress on coffee physiology and production: a review. *Brazilian Journal of Plant Physiology, 18*(1), 55–81. https://doi.org/10.1590/S1677-04202006000100006

Fithriyyah, D., Wulandari, E., & Sendjaja, T. P. (2020). Knowledge level of farmers and the importance of coffee seedling attributes and accessibilities in Bandung Regency, West Java, Indonesia. *Pelita Perkebunan (a Coffee and Cocoa Research Journal), 36*(3), 249–263. https://doi.org/10.22302/iccri.jur.pelitaperkebunan.v36i3.453

Foxx, A. J., & Kramer, A. T. (2020). Variation in number of root tips influences survival in competition with an invasive grass. *Journal of Arid Environments, 179*, 104189. https://doi.org/10.1016/j.jaridenv.2020.104189

Hussain, A., Rizwan, M., Ali, Q., & Ali, S. (2019). Seed priming with silicon nanoparticles improved the biomass and yield while reduced the oxidative stress and cadmium concentration in wheat grains. *Environmental Science and Pollution Research, 26*(8), 7579–7588. https://doi.org/10.1007/s11356-019-04210-5

Jiang, Y., Yang, J., Li, M., Li, Y., Zhou, P., Wang, Q., Sun, Y., Zhu, G., Wang, Q., Zhang, P., & Rui, Y. (2022). Effect of silica-based nanomaterials on seed germination and seedling growth of rice (Oryza sativa L.). *Nanomaterials, 12*(23), 4160. https://doi.org/10.3390/nano12234160

Kamal Kumar, V., Muthukrishnan, S., & Rajalakshmi, R. (2020). Phytostimulatory effect of phytochemical fabricated nanosilver (AgNPs) on Psophocarpus tetragonolobus (L.) DC. seed germination: An insight from antioxidative enzyme activities and genetic similarity studies. *Current Plant Biology, 23*, 100158. https://doi.org/10.1016/j.cpb.2020.100158

Karimian, N., Nazari, F., & Samadi, S. (2021). Morphological and biochemical properties, leaf nutrient content, and vase life of tuberose (Polianthes tuberosa L.) affected by root or foliar applications of silicon (Si) and silicon nanoparticles (SiNPs). *Journal of Plant Growth Regulation, 40*(4), 2221–2235. https://doi.org/10.1007/s00344-020-10272-4

Kim, Y. H., Khan, A., Waqas, M., Shim, J. K., Kim, D. H., Lee, K. Y., & Lee, I. J. (2014). Silicon application to rice root zone influenced the phytohormonal and antioxidant responses under salinity stress. *Journal of Plant Growth Regulation, 33*(1), 137–149. https://doi.org/10.1007/s00344-013-9356-2

Koutouleas, A., Sarzynski, T., Bordeaux, M., Bosselmann, A. S., Campa, C., Etienne, H., Turreira-García, N., Rigal, C., Vaast, P., Ramalho, J. C., Marraccini, P., & Ræbild, A. (2022). Shaded-coffee: A nature-based strategy for coffee production under climate change? A review. *Frontiers in Sustainable Food Systems, 6*, 877476. https://doi.org/10.3389/fsufs.2022.877476

Liang, Y., Hua, H., Zhu, Y. G., Zhang, J., Cheng, C., & Römheld, V. (2006). Importance of plant species and external silicon concentration to active silicon uptake

and transport. *New Phytologist, 172*(1), 63–72. https://doi.org/10.1111/j.1469-8137.2006.01797.x

Lima, A. E., Guimarães, R. J., Cunha, S. H., Castro, E. D., Carvalho, A. M., & Faria, M. M. (2021). Seedling production of Coffea arabica from different cultivars in a modified hydroponic system and nursery using different containers. *Ciência e Agrotecnologia, 45*, e017821. https://doi.org/10.1590/1413-7054202145017821

Nasiro, K. (2017). Germination and seedling growth rate of coffee (Coffea arabica L.) seeds as influenced by initial seed moisture content, storage time and storage condition. *Food Science and Quality Management, 70*, 17–24.

Nile, S. H., Thiruvengadam, M., Wang, Y., Samynathan, R., Shariati, M. A., Rebezov, M., Nile, A., Sun, M., Venkidasamy, B., Xiao, J., & Kai, G. (2022). Nano-priming as emerging seed priming technology for sustainable agriculture—Recent developments and future perspectives. *Journal of Nanobiotechnology, 20*(1), 254. https://doi.org/10.1186/s12951-022-01423-8

Paul, S., Dey, S., & Kundu, R. (2022). Seed priming: An emerging tool towards sustainable agriculture. *Plant Growth Regulation, 97*(1), 215–234. https://doi.org/10.1007/s10725-021-00761-1

Reed, R. C., Bradford, K. J., & Khanday, I. (2022). Seed germination and vigor: Ensuring crop sustainability in a changing climate. *Heredity, 128*(6), 450–459. https://doi.org/10.1038/s41437-022-00497-2

Robinson, J. B. D. (1993). *Coffee in Yemen: A Practical Guide*. Rural Development Project Al-Mahwit Province; Klaus Schwarz Verlag.

Salam, A., Khan, A. R., Liu, L., Yang, S., Azhar, W., Ulhassan, Z., Zeeshan, M., Wu, J., Fan, X., & Gan, Y. (2022). Seed priming with zinc oxide nanoparticles downplayed ultrastructural damage and improved photosynthetic apparatus in maize under cobalt stress. *Journal of Hazardous Materials, 423*, 127021. https://doi.org/10.1016/j.jhazmat.2021.127021

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature Methods, 9*(7), 671–675. https://doi.org/10.1038/nmeth.2089

Seethepalli, A., Dhakal, K., Griffiths, M., Guo, H., Freschet, G. T., & York, L. M. (2021). RhizoVision Explorer: Open-source software for root image analysis and measurement standardization. *AoB Plants, 13*, plab056. https://doi.org/10.1093/aobpla/plab056

Selmar, D., Bytof, G., Knopp, S. E., & Breitenstein, B. (2006). Germination of coffee seeds and its significance for coffee quality. *Plant Biology, 8*(2), 260–264. https://doi.org/10.1055/s-2006-923845

Siddiqui, M. H., Al-Whaibi, M. H., Firoz, M., & Al-Khaishany, M. Y. (2015). Role of nanoparticles in plants. In M. Siddiqui, M. H. Al-Whaibi, & F. Mohammad (Eds.), *Nanotechnology and Plant Sciences: Nanoparticles and Their Impact on Plants* (pp. 19–35). Springer. https://doi.org/10.1007/978-3-319-14502-0_2

Silva, L. O. E., Schmidt, R., Valani, G. P., Ferreira, A., Ribeiro-Barros, A. I., & Partelli, F. L. (2020). Root trait variability in Coffea canephora genotypes and its relation to plant height and crop yield. *Agronomy, 10*(9), 1394. https://doi.org/10.3390/agronomy10091394

Sun, D., Hussain, H. I., Yi, Z., Rookes, J. E., Kong, L., & Cahill, D. M. (2016). Mesoporous silica nanoparticles enhance seedling growth and photosynthesis in wheat and lupin. *Chemosphere, 152*, 81–91. https://doi.org/10.1016/j.chemosphere.2016.02.096

Tripathi, P., Subedi, S., Khan, A. L., Chung, Y. S., & Kim, Y. (2021). Silicon effects on the root system of diverse crop species using root phenotyping technology. *Plants, 10*(5), 885. https://doi.org/10.3390/plants10050885

Tripathi, P., Tayade, R., Mun, B.-G., Yun, B.-W., & Kim, Y. (2022). Silicon application differentially modulates root morphology and expression of PIN and YUCCA family genes in soybean (Glycine max L.). *Frontiers in Plant Science, 13*, 842832. https://doi.org/10.3389/fpls.2022.842832