Original Research Article

Validating protocol and deciphering the nanoparticulate seed treatment in enhancing seed quality of soybean, pigeon pea and groundnut

Abstract

Silicon nanoparticles have attracted huge interest as a rapidly growing class of materials for many agricultural applications. It provided new insight of the potential growth promoting effects of the nanoparticle (SiO_2) on plant system. Looking in to its importance, a comprehensive study was conducted to standardize the protocol on method of seed treatment with Silicon dioxide (SiO_2) nanoparticle for enhancing seed quality in soybean, groundnut and pigeonpea. Among the treatment combinations, soybean, groundnut and pigeonpea seeds treated with SiO_2 nanoparticle in powder form along with polymer found to be superior for all the tested seed quality parameters *viz.*, germination (95.00, 95.33 and 94.67%), seedling length (39.53, 35.17, 25.00cm), mean seedling dry weight (45.53, 28.33 and 50.47mg/seedling), seedling vigour index-I (3759, 3351 and 2368), seedling vigour index-II (4332, 2700 and 4780) for soybean, pigeonpea and groundnut, respectively. However, compared to untreated control, these seed quality attributes were statistically on par with CMC+NP treatment. These findings suggested that seed treatment with SiO_2 nanoparticle in powder form along with polymer coating significantly enhanced seed quality of soybean, groundnut, and pigeonpea.

Keywords: Silicon dioxide, Nanoparticle, Soybean, Groundnut, Pigeonpea and Seed quality

Introduction:

The nanoparticles have been of great scientific value since they came to bridge the gap between bulk materials and atomic / molecular structures, the SiO_2 nanoparticles are most intriguing due to the high surface area by volume ratio, the surface of the nano particles are so important and should be controlled because a change in the size of the surface can generate a change in the physical and chemical properties of the nanoparticles (Khodashenas and Ghorbani, 2015; Barabadi *et al.*, 2020abc). But what factors influence the characteristics of these nanoparticles? What can we do so that their attributes change? When particles reach a size of 1-100nm, their properties change at the electrical, chemical, and physical levels, indicating that the properties are directly related to size, and that changing their size and shape allows for control of properties such as temperature, redox potential, colour, conductivity, chemical stability, electrical qualities, optics, and so on (Du *et al.*, 2020; Sriwuryandari *et al.*, 2020; Bhat *et al.*, 2021). Extensive studies have shown that the size, morphology, stability and properties specifically of the nano silicon dioxide particles are greatly influenced by the experimental conditions of their synthesis, the kinetics of the reaction, the interaction of the ions with the reducing agents and the absorption processes of the stabilizing agent used (Bhat *et al.,* 2021) so that the specific control regarding its shape, size, distribution of the desired nano particle falls on the synthesis method that is selected.

Better seed germination and early seedling establishment are important for increasing production and productivity of soybean, groundnut, and pigeonpea. As a result of producing a deep root system before the top layers of soil dry up, harden, or become exposed to extreme temperatures, rapid and uniform seedling emergence promotes effective establishment. Yet, due to diminished vigour during dry storage especially when kept incorrectly seeds frequently show sluggish and uneven germination. As opposed to conventional approaches, recent uses of certain nanomaterials can speed up plant germination and production and provide excellent plant protection with minimal environmental impact (Siddiqui and Al-Whaibi, 2014; Harish *et al*., 2019). A lot of metabolic and physiological plant processes depend on silicon. When silicon fertilisers are applied to soil that lacks silicon, plants grow more vigorously, become more resistant to disease, cold, and heavy metals like manganese, iron, aluminium, and copper, and as a result, their photosynthesis is enhanced (Khan *et al.,* 2021). By encouraging potassium absorption while inhibiting sodium absorption, silicon fertilisation raises the potassium/sodium selection ratio, aids in the accumulation of potassium, nitrogen, and sulphur in plants, and enhances plant nutrition. In addition to the impact of Si on plant protection, various other beneficial effects of Si have been reported, such as amelioration of the adverse effects of biotic and abiotic stress in plants (Khan *et al*., 2021). SiNPs have physiological features that permit them to penetrate plants, transport into the plant leaves and manipulate plant metabolic actions (Rea *et al.,* 2022).

Surabhi *et al*. (2018) reported that SiO_2 nanoparticle significantly increased pigeonpea germination, field emergence, seedling length, seedling vigour index and lowered electrical conductivity. Similarly, studies discovered that tomato seedlings treated with SiO_2 NPs had improved seed germination (Siddiqui and Al-Whaibi, 2014). Alsaeedi *et al*. (2018)

revealed that exogenous application of nanosilica improves germination and growth of cucumber by maintaining K+/Na+ ratio under elevated salt stress conditions.

Furthermore, researchers have exposed that seed priming techniques may enhance seed germination speed via inducing several biochemical changes in the seed system. These changes are required to start the germination process such as imbibitions and enzyme activation, dormancy breaking, leaching of inhibitors, hydrolysis or breakdown of food reserves and their mobilization, etc. Therefore, the present research was designed to validate the protocol for the seed treatment with Silicon dioxide nanoparticle (SiO_2) for enhancing seed quality in soybean, pigeonpea and groundnut.

Material and Methods:

Seed source

Seeds of soybean cv. JS-335, groundnut cv.GKVK-5 and redgram cv. BRG-5 varieties were obtained from the National Seed Project, University of Agricultural Sciences, Bengaluru and dried to safer and uniform moisture level (< 9%).

Methods of treatments

Upon the confirmation of the properties of nanoparticles through various means, the seeds were subjected to different modes of treatment with Silicon dioxide (SiO_2) at 500ppm concentration to standardize the method of seed treatment for each crop.

Dry treatment: Seeds were treated with Silicon dioxide nanoparticle @ 500ppm by using binding agent Carboxy Methyl Cellulose (CMC). Firstly the seeds were coated with binding agent (CMC), after that powder form of nanoparticle is added and mixed thoroughly for uniform coating and then shade dried for few hours for adequate adhering of chemical.

Wet treatment: The SiO_2 nanoparticle solution is constituted by dispersing the nanopowder in distilled water using the Ultra Sonicator. Then seeds were soaked with the chemical solution for 2 to 6 hours (2h for soybean and Redgram & 6h for groundnut). The treated seeds are then dried under shade for moisture equilibration and uniform absorption of nanoparticles.

Soaking duration for all the crops has been standardized by immersing 2g of seeds in 2ml of water for different durations (1:1 ratio).The duration at which the seeds attained maximum imbibition (uptake of water) without seed coat damage has been considered for further studies. From the study, it is noted that maximum imbibition at 2h for soybean, redgram and 4h for groundnut seeds was obtained without any imbibition injury (Figure 1).

Spray method: About 20g of seeds were placed in petri plates and 0.5ml of nano formulations was sprayed on to the seeds and stirred with glass rod continuously for two minutes to obtain uniform distribution and then shade dried for few hours.

Seed coating: Seeds were subjected to polymer coating @ 3ml/kg seed along with 500mg of SiO_2/kg in powder form using small drum seed treater and then dried under shade. The best form of polymer coating was standardized by coating the seeds both in solution and powder form.

After the different modes of treatments, all the treated seeds were tested by Paper Strip Method (PSM), a special method adapted to record germination and seedling growth without disturbing seedlings. The seed germination along with other parameters was recorded to determine the better mode of seed treatment.

Assessment of Seed quality in the ISTA Member Lab

Treated seeds with three replications were used to determine various quality aspects like seed germination (%) as per ISTA (2021), epicotyl length (cm), hypocotyl length (cm), total shoot length (cm), root length (cm), seedling length (cm), seedling dry weight (mg/seedling), seedling vigour index-I and seedling vigour index-II (Abdul Baki and Anderson, 1973). The mean data obtained were statistically analyzed by using suitable ANOVA and the results were presented as mean ± standard deviation (SD) and by comparing each experimental value with its corresponding control. The critical differences were calculated at five per cent level of probability, wherever ‘F’ test was significant.

Experimental Results:

Final germination percentage (FGP)

Nano seed treatment improved the germination of seeds. Treating SiO_2 nanoparticle with soybean, pigeon pea and groundnut along with polymer coating significantly increased germination (95.00, 94.67 and 95.33%, respectively). On the other hand, it was similar with carboxy methyl cellulose + SiO_2 nanoparticle treatment when compared to untreated control (Table 1, 2 & 3; Fig 2, 3 & 4).

Epicotyl and hypocotyl length of seedling

Similarly, on the first day of germination, imbibitions of water and swelling of the seeds were observed in both control and treated seedlings. On the second day, initiation of sprouting was observed in the treated seedlings as well as the control seeds. On the third day, the length of the sprouts was found to be greater in SiO_2 NPs-treated seeds combined with polymer/CMC as compared to control. On the fourth day, the length of the sprouts increased in the same manner as compared to the seedlings of control following the same trend. The same pattern of growth was also observed on the subsequent days. Thus, the results of the study revealed that among the tested combinations, polymer + NP treatment and CMC + nanoparticle treatment showed the greatest response on the epicotyl lengths (3.10, 11.40, 2.03, cm and 3.20, 10.10, 2.73 cm) and hypocotyl lengths (16.77, 0.27, 3.23cm and 15.03, 0.27, 3.57cm) for soybean, pigeonpea and groundnut, respectively (Table 1, 2 & 3; Fig 2, 3 & 4).

Mean Seedling length

Nano seed treatment improved the seedling length of plant system. Treating of soybean, pigeon pea and groundnut seeds with SiO_2 nanoparticle with along with polymer coating significantly increased seedling length (39.53,35.17 and 25.00cm). On the other hand, it was similar to carboxymethyl cellulose + SiO_2 nanoparticle treatment (37.47, 31.00 and 23.70 cm respectively) when compared to control (Table 1, 2 & 3; Fig 2, 3 & 4).

Mean Seedling dry weight

Seedling dry weight found to be significantly higher in polymer + nanoparticle treatment (45.53, 28.33 and 50.47 mg/seedling) and carboxymethyl cellulose + SiO_2 nanoparticle treatment (41.57, 26.40 and 48.77 mg/seedling) when compared to any other treatments in soybean, pigeon pea and groundnut, respectively.

Seedling vigour index I and II

Mean seedling vigour indices also increased significantly due to nano-particle treatments. In soybean, pigeonpea and groundnut, seedling vigour index I (SVI-I) improved significantly with polymer + nanoparticle treatment (3759, 3351 and 2368) and carboxymethyl cellulose + SiO_2 nanoparticle treatment (3563, 2954 and 2244), when compared to control (3120, 2412, 1574). Even seedling vigour index II (SVI-II) also resulted in significant improvement with polymer + nanoparticle treatment (4332, 2700 and 4780) and carboxymethyl cellulose + SiO_2 nanoparticle treatment (3955, 2515 and 4619), when compared to control (3260, 2033, 3368) in all the three crops, respectively.

Discussion:

The data depicted in **Tables 1 to 3** elucidated that SiNPs treatment along with polymer/ carboxy methyl cellulose succeeded to enhance germination and seedling growth development of soybean, pigeonpea and groundnut seedlings recording higher values for germination and its parameters in contrast to untreated seeds.

Moreover, another possible elucidation for improving germination and vigour via SiNPs might be owing to the ability of SiNPs to initiate some biochemical processes inside the seed system after easily piercing through seed coat because of tiny size of silica nanoparticles (Alsaeedi *et al*., 2017). Besides, SiNPs found responsible in removing the free radicals, which inhibit the germination after entering in to the seed. As a result, it activates CAT and SOD enzymes by alerting some oxidation-reduction reactions and thereby produce superoxide ion radical which have an important role in nullifying the free radicals found inside the seed and finally enhance the germination (Gengmao *et al*., 2015). Moreover, SiNPs can be crucial in releasing the dormancy of seeds by increasing gibberellin secretion and reducing the formation of abscisic acid (Yuvakkumar *et al*., 2011). To underline these results in the open field, however, additional research is required. This is because SiNPs may undergo some alterations or transformations when put into a complex and open system like the interactions between soil and the environment. Also, considerable biochemical and physiological research is required to clearly define the alterations that could occur within the plant cell as a result of SiNPs treatment. Previous research has revealed at least three mechanisms. The first of these most likely takes place at the level of the control of gene expression. Aquaporins are transmembrane proteins that help biological membranes transport gases and water as well as reactive oxygen species (ROS). "Si" nanoparticles activate the genes that code for these proteins (Maurel *et al*., 2015). The second takes place when gibberellins activate the production of gibberellins and hydrolytic enzymes such - amylase, proteases, and lipases (Feregrino-Perez *et al*., 2018). These enzymes facilitate the hydrolysis of organic compounds with larger molecular weights into molecules with lower molecular weights that serve as respiratory substrates for developing cells. Moreover, when the concentration of monosaccharides and other low-molecular-weight compounds rises, the osmotic potential of cells rises, hastening the absorption of seed structures and other storage materials. The link between the amount of oxidative stress and the activity of the antioxidant system in the embryonic cells may vary as a result of the third mode of action of SiNPs (Mahakham *et al*., 2017, Kibinza *et al*., 2011). Plant cells' antioxidant enzymes (catalase and superoxide dismutase) are activated as a result of stimulation of the production of reactive oxygen species (ROS) such hydrogen peroxide and hydroxyl radicals by SiNPs. These modifications set the proper quantity of ROS in embryonic cells, forming the so-called "Oxidative window," which is required to activate signal pathways that start seed germination and promote improved seedling growth and development.

Conclusion:

This paper discusses the role of powder form of nanosilica (SiNPs) particles to enhance seed germination of soybean, pigeon pea and groundnut and the development of seedlings (vigour) under controlled conditions in paper strip method. The outlined data revealed that seed treatment with SiO_2 nanoparticle along with polymer or carboxy methyl cellulose conspicuously improved seed germination and accelerated the seedling growth and development. Further, all the measured parameters of germination and growth of seedlings of all three crops were appreciably superior over untreated control. Besides, application of Silicon dioxide (SiO_2) in nanoform may facilitate better penetration inside the seed due to its nano-size and consequently alerting various biochemical processes such as elimination free radicals by activating CAT and SOD enzymes. Therefore, in the future, such amendments (SiNPs) could be advocated into the guidelines of good agricultural practices to improve crop growth and productivity.

Table 1. Influence of seed treatment methods with SiO_2 nanoparticle on seed germination and vigour by PSM method in soybean

Treatments	Germination (%)	Epicotyl length (cm	Hypocotyl length (cm)	Shoot length (cm)	Root length (cm)	Seedling length (cm)	Seedling dry weight (mg/seedling)	SVI-I	SVI-II
Control	90.33	1.97	15.43	17.50	17.03	34.53	36.03	3120	3260
Polymer	85.33	2.10	14.53	16.60	18.73	35.33	40.53	3018	3464
Polymer + NP (P)	95.00	3.10	16.77	19.80	19.73	39.53	45.53	3759	4332
Polymer + NP (S)	85.33	2.10	16.23	18.30	18.23	36.53	39.07	3121	3339
Nano spray	90.33	2.47	14.50	16.93	17.23	34.17	39.07	3090	3534
CMC + NP	95.00	3.20	15.03	18.20	19.27	37.47	41.57	3563	3955
Soaking/wet methods	93.00	2.30	15.73	17.97	17.13	35.10	39.07	3268	3639
Mean	**90.62**	**2.46**	**15.46**	**17.90**	**18.20**	**36.10**	40.12	**3277**	**3646**
S.Em±	2.33	0.10	0.25	0.56	0.39	0.73	1.18	145.76	197.46
CD(0.05P)	7.08	0.31	0.76	1.69	1.19	2.21	3.58	442.10	598.93
CV(%)	4.46	7.15	2.81	5.39	3.75	3.45	5.09	7.70	9.38

Note: NP (P)-SiO_2 nanoparticle in powder form, NP(S) - SiO_2 nanoparticle in solution form, No Hard and FUG seeds observed, PSM-Paper strip method, SVI-I: Seedling Vigour index-I; SVI-II: Seedling Vigour index-II

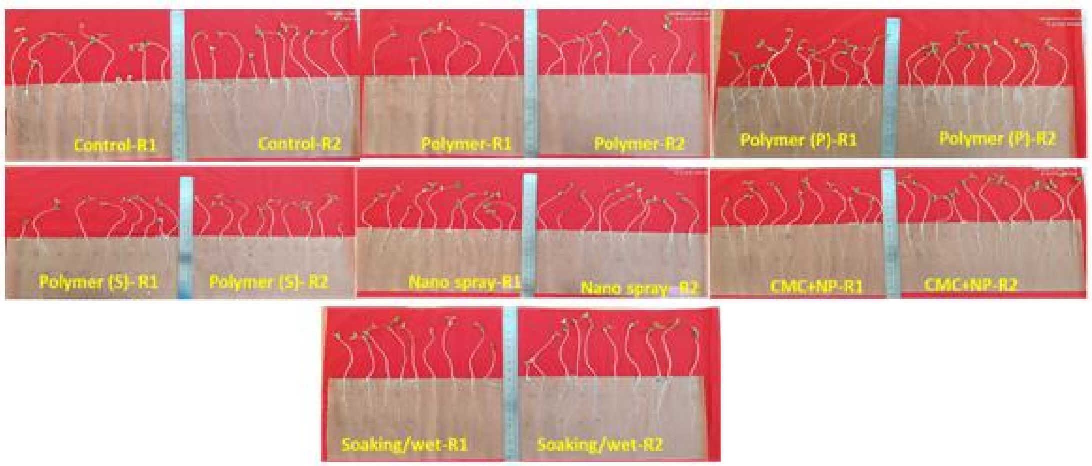

Figure 1. Influence of seed treatment with SiO_2 nanoparticle on germination of soybean seeds in paper strip method

Table 2. Influence of seed treatment methods with SiO_2 nanoparticle on germination and seedling vigour by PSM method in pigeonpea

Treatments	Germination (%)	Epicotyl length (cm)	Hypocotyl length (cm)	Shoot length (cm)	Root length (cm)	Seedling length (cm)	Seedling dry weight (mg/seedling)	SVI-I	SVI-II
Control	85.00	8.57	0.23	8.83	19.57	28.40	23.93	2412	2033
Polymer	85.33	8.77	0.27	9.00	20.07	29.07	22.47	2479	1916
Polymer + NP (P)	95.33	11.40	0.27	11.70	23.47	35.17	28.33	3351	2700
Polymer + NP (S)	85.33	8.90	0.27	9.17	16.43	25.60	25.37	2183	2163
Nano spray	80.00	8.60	0.27	8.90	19.10	28.00	24.93	2239	1993
CMC + NP	95.33	10.10	0.27	10.37	20.63	31.00	26.40	2954	2515
Soaking/wet methods	95.33	9.90	0.30	10.20	21.13	31.33	25.90	2986	2468
Mean	**88.81**	**9.46**	**0.27**	**9.74**	**20.06**	**29.80**	**25.33**	**2658**	**2256**
S.Em±	1.58	0.16	0.03	0.27	0.49	0.75	0.59	54.08	39.88
CD(0.05P)	4.80	0.50	0.09	0.82	1.48	2.28	1.79	164.04	120.96
CV(%)	3.09	3.01	20.04	4.79	4.22	4.38	4.03	3.53	3.06

Note: NP (P)-SiO_2 nanoparticle in powder form, NP(S) - SiO_2 nanoparticle in solution form, No Hard and FUG seeds observed, PSM-Paper strip method, SVI-I: Seedling Vigour index-I; SVI-II: Seedling Vigour index-II

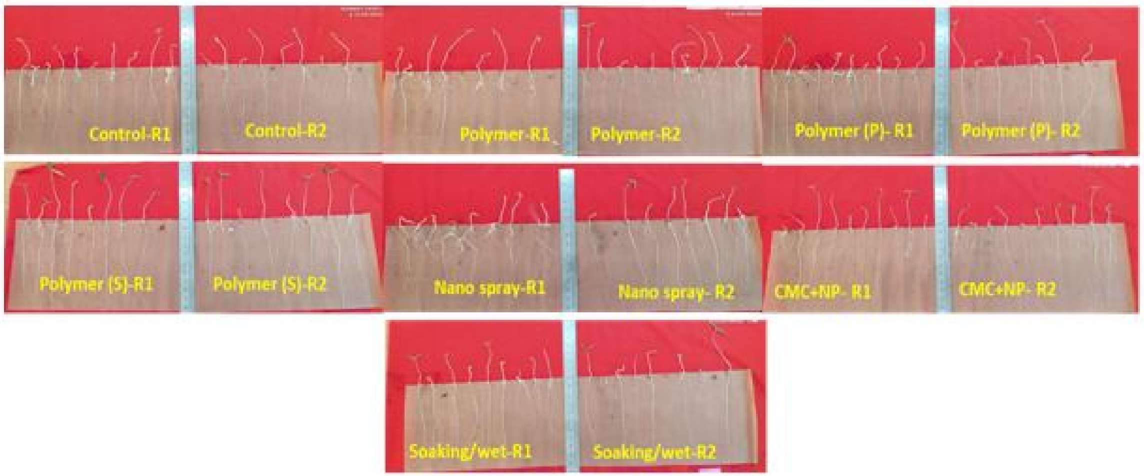

Figure 2. Influence of seed treatment with SiO_2 nanoparticle on germination of pigeonpea seeds in paper strip method

Table 3. Influence of seed treatments method with SiO_2 nanoparticle on seed germination and vigour by PSM method in groundnut

Treatments	Germination (%)	Epicotyl length(cm)	Hypocotyl length (cm)	Shoot length (cm)	Root length (cm)	Seedling length (cm)	Seedling dry weight (mg/seedling)	SVI-I	SVI-II
Control	80.67	1.20	2.97	4.33	15.25	19.50	41.73	1574	3368
Polymer	70.00	1.37	2.47	4.50	18.07	22.57	37.90	1580	2654
Polymer + NP (P)	94.67	2.03	3.23	4.70	20.30	25.00	50.47	2368	4780
Polymer + NP (S)	80.67	1.47	2.67	4.23	15.60	19.83	39.87	1600	3217
Nano spray	80.67	1.57	2.83	5.57	18.30	23.97	40.83	1925	3294
CMC + NP	94.67	2.73	3.57	5.53	18.17	23.70	48.77	2244	4619
Soaking/wet methods	95.00	1.97	3.03	3.03	18.17	21.20	49.80	2013	4730
Mean	**85.19**	**1.76**	**2.97**	**4.56**	**17.69**	**22.24**	**44.20**	**1901**	**3809**
S.Em±	1.23	0.05	0.07	0.06	0.46	0.48	1.01	55.27	123.90
CD(0.05P)	3.72	0.15	0.20	0.18	1.40	1.47	3.08	167.64	375.81
CV(%)	2.50	4.80	3.89	2.30	4.51	3.76	3.98	5.04	5.63

Note: NP (P)-SiO_2 nanoparticle in powder form, NP(S) - SiO_2 nanoparticle in solution form, No Hard and FUG seeds observed, PSM-Paper strip method, SVI-I: Seedling Vigour index-I; SVI-II: Seedling Vigour index-II

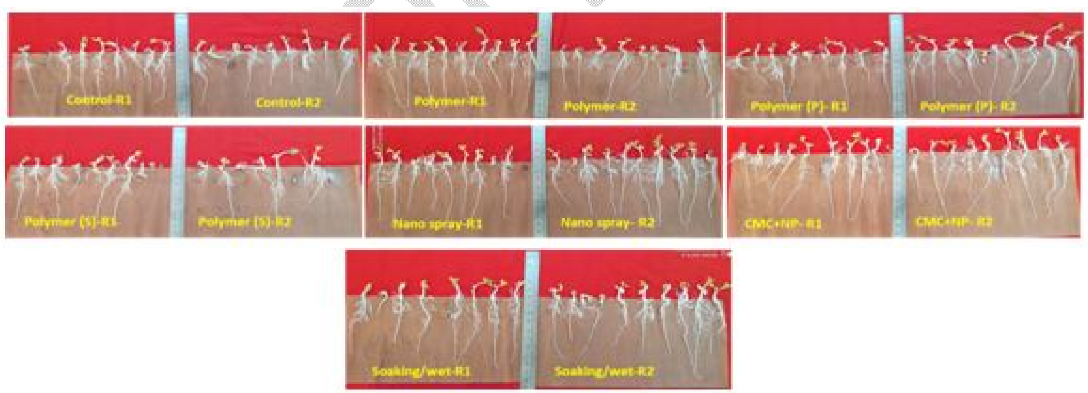

Figure 3. Influence of seed treatment with SiO_2 nanoparticle on germination of groundnut seeds in paper strip method

References:

Abdul Baki, A. A. and Anderson, J. D. (1973). Vigour determination of soybean seeds by multiple criteria. *Crop Sci*., **13**: 630-633.

Alsaeedi, A. H., El-Ramady, H., Alshaal, T., El-Garawani, M., Elhawat, N. and Almohsen, M. (2017). Engineered silica nanoparticles alleviate the detrimental effects of Na+ stress on germination and growth of common bean (*Phaseolus vulgaris*). *Environ. Sci. Pollut. Res.*, **24**: 21917-21928.

Alsaeedi, A., El-Ramady, H., Alshaal, T., El-Garawani, M., Elhawat, N. and Al-Otaibi, A. (2018). Exogenous nanosilica improves germination and growth of cucumber by maintaining K+/Na+ ratio under elevated Na+ stress. *Plant Physiol. Biochem.*, **125**: 164-171.

Barabadi, H., Hosseini, O., DamavandiKamali, K., JazayeriShoushtari, F., Rashedi, M., Haghi-Aminjan, H. and Saravanan, M. (2020a). Emerging theranostic silver nanomaterials to combat lung cancer: a systematic review. *J. Clust. Sci.*, **31**: 1-10.

Barabadi, H., Vahidi, H., Damavandi Kamali, K., Hosseini, O., Mahjoub, M. A., Rashedi, M., JazayeriShoushtari, F. and Saravanan, M. (2020b). Emerging theranostic gold nanomaterials to combat lung cancer: a systematic review. *J. Clust. Sci*., **31**: 323-330.

Barabadi, H., Vahidi, H., DamavandiKamali, K., Rashedi, M., Hosseini, O. and Saravanan, M. (2020c). Emerging theranostic gold nanomaterials to combat colorectal cancer: a systematic review. *J. Clust. Sci*., **31**(4): 651-658.

Bhat, J. A., Rajora, N., Raturi, G., Sharma, S., Dhiman, P., Sanand, S., Shivaraj, S., Sonah, H. and Deshmukh, R. (2021). Silicon nanoparticles (SiNPs) in sustainable agriculture: Major emphasis on the practicality, efficacy and concerns. *Nanoscale Adv.*, **3**(14): 4019-4028.

Das, D., Yang, Y., O'Brien, J. S., Breznan, D., Nimesh, S., Bernatchez, S., Hill, M., Sayari, A., Vincent, R. and Kumarathasan, P. (2014). Synthesis and physicochemical characterization of mesoporous SiO_2 nanoparticles. *J. Nanomater*., **62**(6): 11-12.

Djangang, C. N., Mlowe, S., Njopwouo, D. and Neerish, R. (2015). One-step synthesis of silica nanoparticles by thermolysis of rice husk ash using non toxic chemicals ethanol and polyethylene glycol. *J. Appl. Chem.*, **4**(4), 1218-1226.

Du, D., Jiang, Y., Feng, J., Li, L. and Feng, J. (2020). Facile synthesis of silica aerogel composites via ambient-pressure drying without surface modification or solvent exchange. *Vacuum*, **173**: 109117.

Feregrino-Perez, A. A., Magaña-López, E., Guzmán, C. and Esquivel, K. (2018). A general overview of the benefits and possible negative effects of the nanotechnology in horticulture. *Sci. Hortic.*, **238**: 126-137.

Gengmao, Z., Shihui, L., Xing, S., Yizhou, W. and Zipan, C. (2015). The role of silicon in physiology of the medicinal plant (*Lonicera japonica* L.) under salt stress. *Sci. Rep.*, **5**(1), 1-11.

Harish, M. S., Gowda, R. and Nethra, N. (2019). Standardization of nano particles for enhancing groundnut seed quality Cv. ICGV-91114. *J. pharmacogn. phytochem.*, **8**(1): 2208-2212.

ISTA. (2021). International Rules for Seed Testing. *Seed Sci.* and *Technol.*, **27**: 25-30.

Khan, I., Awan, S. A., Rizwan, M., Ali, S., Hassan, M. J., Brestic, M., Zhang, X. and Huang, L. (2021). Effects of silicon on heavy metal uptake at the soil-plant interphase: A review. *Ecotoxicol. Environ. Saf.*, **222**: 112510.

Khodashenas, B. and Ghorbani, H. R. (2019). Synthesis of silver nanoparticles with different shapes. *Arab. J. Chem.*, **12**(8): 1823-1838.

Kibinza, S., Bazin, J., Bailly, C., Farrant, J. M., Corbineau, F. and El-Maarouf-Bouteau, H. (2011). Catalase is a key enzyme in seed recovery from ageing during priming. *Plant Sci.*, **181**(3), 309-315.

Mahakham, W., Sarmah, A. K., Maensiri, S. and Theerakulpisut, P. (2017). Nanopriming technology for enhancing germination and starch metabolism of aged rice seeds using phytosynthesized silver nanoparticles. *Sci Rep*., **7**(1): 8263.

Maurel, C., Boursiac, Y., Luu, D. T., Santoni, V., Shahzad, Z. and Verdoucq, L. (2015). Aquaporins in plants. *Physiol. Rev*., **95**(4): 1321-1358.

Molpeceres, J., Aberturas, M. R. and Guzman, M. (2000). Biodegradable nanoparticles as a delivery system for cyclosporine: preparation and characterization. *J Microencapsul.*, **17**(5): 599-614.

Mourhly, A., Khachani, M., Hamidi, A. E., Kacimi, M., Halim, M. and Arsalane, S. (2015). The synthesis and characterization of low-cost mesoporous silica SiO_2 from local pumice rock. *Nanomater. Nanotechnol.*, **5**: 35.

Rea, R. S., Islam, M. R., Rahman, M. M., Nath, B. and Mix, K. (2022). Growth, nutrient accumulation, and drought tolerance in crop plants with silicon application: a review. *Sustainability*, **14**(8): 4525.

Siddiqui, M. H. and Al-Whaibi, M. H. (2014). Role of nano-SiO_2 in germination of tomato (*Lycopersicum esculentum* seeds Mill.). *Saudi J. Biol. Sci.*, **21**(1): 13-17.

Sriwuryandari, L., Priantoro, E. A., Janetasari, S. A., Butar, E. B. and Sembiring, T. (2020). Utilization of rice husk (*Oryza sativa*) for amorphous biosilica (SiO_2) production as a bacterial attachment. *IOP Conf. Ser. Earth Environ. Sci*., **483** (1): 012023.

Surabhi, V. K., Rame, G. and Nethra, N. (2018). Standardization of seed treatment protocol with nanoparticles for enhancing seed quality in pigeonpea. *Mysore J. Agric. Sci*., *52*(3): 588-596.

Yuvakkumar, R., Elango, V., Rajendran, V., Kannan, N. S. and Prabu, P. (2011). Influence of nanosilica powder on the growth of maize crop (*Zea mays* L.). *Int. J. Green Nanotechnol. Biomed.*, **3**(3): 180-190.

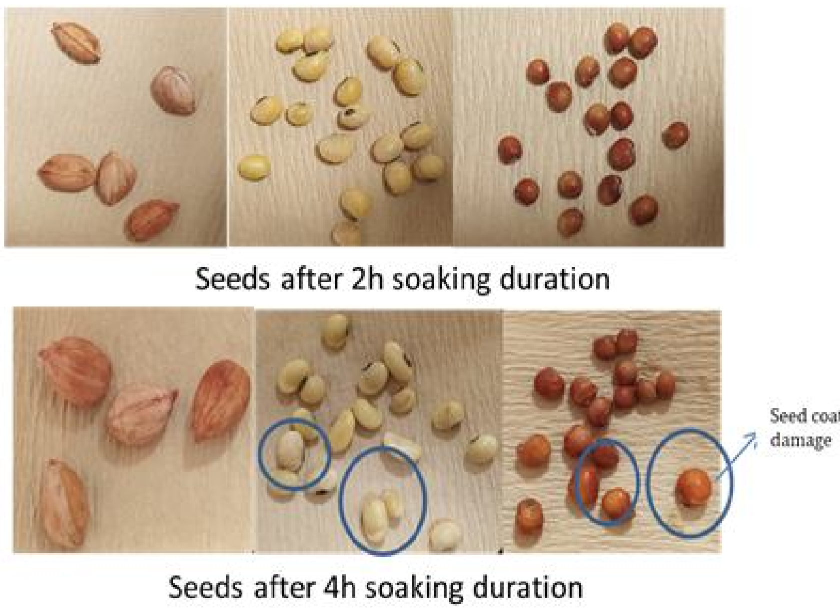

Fig 4. Seed imbibition studies to optimize the duration of soaking in groundnut, soybean and pigeonpea