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Tailoring Nanoparticle Formulation for Maize Seed Quality Improvement through Multiple Approaches

K. Ezhilarasan[1], Rame Gowda[2], Basave Gowda[3], T. M. Ramanappa[4], C. Manja Naik[5], N. Nethra[6], B. Roopashree[7] and K. Umarani[8]

[1&3]Department of Seed Science and Technology, Collge of Agriculture, UAS, GKVK, Bengaluru - 560 065

[2,4,5,6,7&8]Seed Technology Research Unit, AICRP on Crops (Seeds), UAS, GKVK, Bengaluru - 560 065

e-Mail : arasane30@gmail.com

Authors Contribution

K. Ezhilarasan & Rame Gowda : Conceptualization, conducted experiment and drafted manuscript;

Basave Gowda; T. M. Ramanappa; C. Manja Naik & N. Nethra : Contribution for experimental materials, labouratory support and manuscript correction;

B. Roopashree & K. Umarani : Literature review, assisted in conducting experiments and data analysis

Corresponding Author :

K. Ezhilarasan : Department of Seed Science and Technology, UAS, GKVK, Bengaluru

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Abstract

This study was aimed to make use of nanotechnology as it facilitates the seed quality attributes and improved production through multiple approaches in maize (*Zea mays* L.). Laboratory experiments were conducted on maize *cv.* MAH 14-138 hybrid seeds treated with five different nano and bulk chemicals *i.e.,* Silicon dioxide (SiO_2), Titanium dioxide (TiO_2), Zinc oxide (ZnO), Iron oxide (FeO) and Sulphur (S) to assess their performance along with seed treatment methods v*iz.,* dry dressing, polymer mediated coating and wet soaking. The results of the study showed that dry dressing of SiO_2 NPs @ 500 & 1000 mg/kg and TiO_2 NPs @ 1000 mg/kg of seeds recorded significantly higher germination (100%) compared to untreated control (92%) and bulk SiO_2 @ 500 & 1000 mg/kg registered (97 and 88%, respectively). However, the seedling length (40.20 cm), seedling dry weight (80.51 mg/seedling), seedling vigour index-I (3968) and seedling vigour index-II (7945) were significantly superior in polymer mediated coating with SiO_2 NPs @ 1000 mg/kg of seeds over untreated control (28.90 cm, 47.09 mg/seedling, 2649 and 4316, respectively) followed by bulk SiO_2 1000 mg/kg (36.45 cm, 71.37 mg/seedling, 3560 and 6970, respectively). Further, highest total dehydrogenase activity (0.853) was recorded in polymer coated with SiO_2 NPs @ 1000 mg/kg of seeds when compared to untreated control (0.487) and polymer coated with bulk SiO_2 @ 1000 mg/kg (0.765) and the lowest electrolyte leachate (9.36 µS/cm/g) recorded in dry dressing with TiO_2 NPs @ 1000 mg/kg of seeds. Therefore, nano coating with SiO_2 or TiO_2 NPs at the concentrations of 500 mg/kg of seeds by either dry dressing or polymer coating method found to improve the seed quality of maize hybrid when compared to their respective bulk form of chemicals and these techniques could be suggested to enhance the quality of maize seeds.

Keywords : Nanochemicals, Maize hybrid, Dry dressing, Polymer coating & seed quality

Maize (*Zea mays* L.) is the most genetic diverse of any other cereal crops, which is farmed in many regions of the world. About 165 countries having wide range of soil, climate and biodiversity, maize contributes about 39 per cent of the global grain production (Anonymous, 2020). Around 74.5 per cent of maize kernels are carbohydrate, 10 per cent are protein, 3.4 per cent are oil and the rests is made up of fibre, vitamins and minerals (Paliwal *et al*., 2000). It has a wide range of uses because of its widespread availability and relative affordability. Used for direct human consumption, livestock feeding, industrial food processing and industrial non-food items like starches, acids and alcohols. In India, maize is being cultivated in 9.86 million hectares with a production of 31.51 million tonnes with productivity rate of 3195 kg/ hectare. Among all states, Karnataka holds first place in maize production with 1.68 million hectares of area.

This is about 17.0 per cent of India's total area under cultivation, producing around 5.18 million tonnes which is 16.45 per cent of all India production with a yield of 3092 kg/hectare (Anonymous 2021).

Nanotechnology, the advanced modern tool in various branches and also it has the greater potential to increase the agricultural productivity through genetic improvement, nanoparticles ensured seed quality, nano based inputs and protectants, new solutions for soil and water remediation, nano based technologies to reduce biotic and abiotic stresses. This can reduce the impacts due to agricultural production against the environment significantly through eco-friendly alternative nano molecules. Khalaki *et al.* (2020) reported that seed priming with nanoparticles also negatively influenced as inhibition of germination and genotoxicity or genetic changes, which are highly selective and concentration specific. The positive effects depend on nanoparticle physio-chemical properties such as size, zeta potential and concentrations and formulation which are factors that determine the biological responses. These acts as stimulants, improving seed metabolism, seedling vigour and plant growth by acting in cellular signalling pathways (Acharya *et al.*, 2020). Priming with nanochemicals amended with the early germination by activating phyto-hormones, increased germination percentage, plant growth, seed health, protection at stored seeds, tolerates both insect pests and abiotic stress conditions and reduces the usage of pesticides and conventional fertilizers (Mahakham *et al.*, 2017).

Seeds treated with metallic nanochemicals such as silicon dioxide, titanium dioxide, iron oxide, etc., which are highly active and polymeric nanochemicals providing slow release of active compounds to modify plant metabolism. Seed coating with zinc oxide and iron oxide nanoparticles improved plant development at high concentrations, increased spike length, plant biomass, chlorophyll contents and photosynthetic parameters in leaves (Rizwan *et al.*, 2019). Kasote *et al.* (2019) studied that watermelon seeds primed with iron nanoparticles synthesized from onion extracts showed that increased germination and growth of shoots and roots. Seed coated with nanochemicals which may promote the ROS production, acting in different metabolic pathways, increase the level of active gibberellins and the mobilization of storage proteins. Ahuja *et al.*, (2019) demonstrated that iron (II) sulfide nanoparticles were more effective than the fungicide carbendazim to control the fungus *Fusarium verticillioides* in rice seeds. Therefore, with these indications, the standardization of different bulk and nanochemicals for seed quality enhancement of Maize hybrid MAH 14-138 was undertaken at the Seed Technology Research Unit, All India Co ordinate Research Project on Seed (Crops), University of Agricultural Sciences, Gandhi Krishi Vingnana Kendra, Bengaluru to study the influence of nanochemicals with that of bulk forms on maize seed quality improvement.

Material and Methods

Seeds of Maize Hybrid MAH 14-138 were procured from National Seed Project (Crops), University of Agricultural Sciences, GKVK, Bengaluru and laboratory experiment was conducted in Seed Technology Research Unit, NSP, UAS, GKVK, Bengaluru - 560 065, during *kharif*, 2022. The seeds were dried to attain optimum moisture content of 9 per cent and utilized for the experiment. About one kilogram of seeds in each treatment were treated by three different methods with both bulk and nano forms of selected chemicals *viz.,* Silicon dioxide (SiO_2), Titanium dioxide (TiO_2), Zinc oxide (ZnO), Iron oxide (FeO) and Sulphur (S) obtained from Sigma Aldrich Chemicals Ltd. The particle size of these selected nanochemicals was ascertained and it was less than 100nm. The seed treatment methods adopted is described below.

Dry Dressing : One kilogram of seeds were treated with five different selected chemicals *viz.,* Silicon dioxide (SiO_2), Titanium dioxide (TiO_2), Zinc oxide (ZnO), Iron oxide (FeO) and Sulphur (S) in both bulk and nano forms at the concentrations of 250, 500, 750 and 1000 mg/kg of seeds. About 2 to 3 ml of 2 per cent carboxy methyl cellulose (CMC) /kg of seeds used as binding agent for uniform coating and the treated seeds were air dried to bring back the original moisture content under room temperature.

Polymer Mediated Coating : One kilogram of seeds were coated through synthetic polymer (pink) @ 3 ml/kg of seeds along with both of bulk and nano chemicals with different concentrations *i.e.,* 250, 500, 750 and 1000 mg/kg of seeds and the untreated seeds served as control. Further, the treated seeds were shade dried under room temperature to bring back original moisture content.

Wet Soaking Method : Seeds of required quantity (one kg each) were surface sterilized with 0.2 per cent Sodium hypochlorite solution for a minute and rinsed thoroughly with distilled water in order to remove seed coat infection, if any, then dried to obtain safe moisture level. Nano chemicals were dissolved in distilled water by means of sonication and then the seeds were soaked in the solution for 16 hours for both bulk and nano form soaking treatments. Then, the seeds were dried to original moisture content and evaluated for initial seed quality parameters.

Treatment details

Methods	Bulk form of chemicals	Nano chemicals	Concentrations
M_1 - Dry Dressing	B_1 - SiO_2	N_1 - SiO_2	C_1 - Control (untreated)
M_2 - Polymer mediated coating	B_2 - TiO_2	N_2 - TiO_2	C_2 - 250 mg
M_3 – Wet soaking	B_3 - ZnO	N_3 - ZnO	C_3 - 500 mg
	B_4 - FeO	N_4 - FeO	C_4 - 750 mg
	B_5 - S	N_5 - S	C_5 - 1000 mg

Experimental Design : Factorial Completely Randomized Design with Three Replications

Seed Quality Testing : Seed quality parameters like standard germination (%), seedling length and seedling dry weight, electrical conductivity of seed leachate and total dehydrogenase activity were determined as indicated below.

- Standard seed germination by between paper methods described by ISTA (2021)
- Seedling vigour indices were computed as per Abdul - Baki and Anderson (1973)
- Seedling vigour index-I (SVI-I) = Germination (%) x Mean seedling length (cm)
- Seedling vigour index-II (SVI-II) = Germination (%) x Mean seedling dry weight (mg)
- Electrical conductivity (EC) of seed leachate (ISTA, 1998)
- Total dehydrogenase activity (TDA) as per the method described by Kittock and Law (1968).

Results and Discussion

In the present investigation, application of different nano and bulk form of chemicals as seed coating agents showed that the seed coated with nanochemicals at different concentrations performed better over their respective bulk form of chemicals in improvement of seed quality attributes (Fig.1 & 2). Among the different treatment methods, dry dressing recorded significantly higher germination (100%) in SiO_2 NPs @ 500 & 1000 mg/kg of seeds but it was on par with TiO_2 NPs @ 500 and 1000 mg/ kg of seeds (99 and 100%, respectively). But even in

Fig. 1. Germination pattern of treated seeds with nanochemicals in maize hybrid (MAH-14-138)

Fig. 2 : Depicting seedling growth (a) and seedling vigour (b) due to seed treatment with nanochemicals in (MAH-14-138) maize hybrid

polymer mediated coating method, the germination was significantly superior (99%) with SiO_2 NPs @ 1000 mg/kg of seeds which was closely followed by TiO_2 NPs @ 500 & 1000 mg/kg of seeds, but the germination was lowest (92%) in untreated control and bulk form of SiO_2 @ 1000 mg/kg (98%). Conversely, in wet soaking method, the germination was recorded maximum (98%) in Sulphur NPS @ 500 mg/kg of seeds when compared to bulk form of Sulphur @ 500 mg/kg and untreated control (96 & 97%, respectively) (Tables 1, 3 & 5). Seedling length (40.20 cm) was significantly higher in seeds of polymer coated with SiO_2 NPs @ 1000 mg/kg and it was on par with dry dressing of TiO_2 NPs @ 1000 mg/kg of seeds, but it was significantly lower in wet soaking treatment with SiO_2 & TiO_2 NPs @ 1000 mg/kg (30.09 and 27.35 cm, respectively), polymer coated with bulk form of SiO_2 and dry dressing with bulk form of TiO_2 @ 1000 mg/kg (36.45 and 33.57 cm, respectively) and untreated control (23.62 cm). These quality attributes are illustrated in Fig. 3a, 4a & 5a. The seedling dry weight was significantly higher (80.51 mg/seedling) in polymer coated seeds with SiO_2 NPs @ 1000 mg/kg and in dry dressing with ZnO NPs @ 1000 mg/kg of seeds (79.15 mg/seedling) over wet soaking of SiO_2 and ZnO NPs @ 1000 mg/kg of seeds (59.77 and 57.03 mg/seedling, respectively) but it was lowest in untreated control (47.09 mg/seedling). Both polymer coated and dry dressed seeds with bulk form of SiO_2 @ 1000 mg/kg and ZnO @ 1000 mg/kg recorded slightly lower seedling dry weights (71.37 mg and 57.30 mg, respectively), which are depicted in Fig. 3b, 4b & 5b. Therefore, these findings suggested that the mode of seed treatment with type of nanochemicals and their concentrations play a significant role in enhancing the seed quality in maize. The reason being since the nanochemicals can easily penetrate into the seed, stimulates the enzyme

TABLE 1

Effect of dry dressing seed treatment with selected nano and bulk form of chemicals on germination (%) in maize hybrid *cv.* MAH 14-138

Treatments	Chemicals (N) both nano and bulk form					
	SiO_2	TiO_2	ZnO	FeO	S	Mean
F_1	92	97	98	96	99	96.4
F_2	92	97	97	95	93	94.8
Mean	92.0	97.0	97.5	95.5	96	95.5
Concentration (C)						
C_1	92	92	92	92	92	92.0
C_2	98	98	96	95	99	97.2
C_3	99	98	98	97	97	97.8
C_4	92	97	97	95	98	95.8
C_5	94	98	95	96	98	96.2
Mean	95.0	96.6	95.6	95.0	96.8	95.5
Interaction (F x C)						
F_1C_1	92	92	92	92	92	92.0
F_1C_2	97	98	96	96	99	97.2
F_1C_3	100	99	97	96	99	98.2
F_1C_4	99	95	95	93	98	96.0
F_1C_5	100	100	99	97	99	99.0
F_2C_1	92	92	92	92	92	92.0
F_2C_2	98	98	96	93	98	96.6
F_2C_3	97	96	99	98	96	97.2
F_2C_4	85	98	98	98	98	95.4
F_2C_5	88	96	91	94	97	93.2
Mean	94.8	96.4	95.5	94.9	96.8	95.5

	S.Em ±	CD (0.05P)	CV (%)
F	0.18	0.50	
N	0.28	0.79	
C	0.18	0.50	
F x N	0.40	1.11	1.61
F x C	0.69	1.93	
N x C	0.63	1.76	
F x N x C	0.89	2.49	

Treatment details :

F_1 – Nano chemicals C_1 – Control C_4 – 750 ppm
F_2 –Bulk chemicals C_2 – 250 ppm C_5 – 1000 ppm
C_3 – 500 ppm

TABLE 2

Effect of dry dressing seed treatment with selected nano and bulk form of chemicals on seed vigour index-II in maize hybrid cv. MAH 14-138

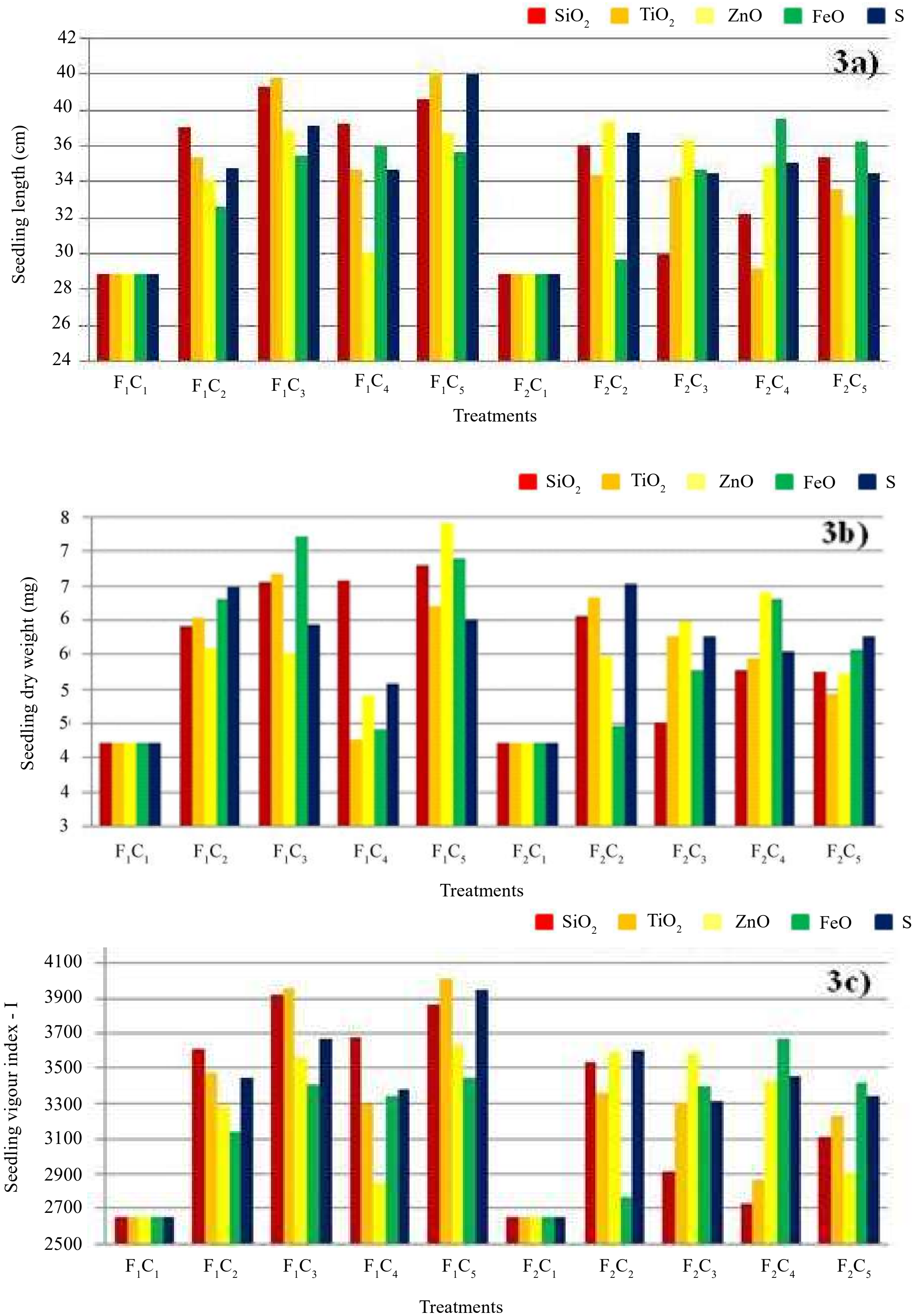
Treatments	Chemicals (N) both nano and bulk form					
	SiO_2	TiO_2	ZnO	FeO	S	Mean
F_1	4316	6401	6743	5332	7072	5973
F_2	4316	6064	5791	6014	5453	5528
Mean	4316	6233	6267	5673	6262	5750
Concentration (C)						
C_1	4316	4316	4316	4316	4316	4316
C_2	6335	6534	5795	5596	6905	6233
C_3	5951	6572	6105	6526	6181	6267
C_4	5935	5184	5941	5611	5693	5673
C_5	6169	5967	6503	6428	6246	6262
Mean	5741	5714	5732	5695	5868	5750
Interaction (F x C)						
F_1C_1	4316	4316	4316	4316	4316	4316
F_1C_2	6250	6412	5866	6563	6916	6401
F_1C_3	7019	7122	5820	7405	6347	6743
F_1C_4	6984	4525	5127	4579	5444	5332
F_1C_5	7285	6713	7810	7131	6420	7072
F_2C_1	4316	4316	4316	4316	4316	4316
F_2C_2	6421	6655	5724	4628	6894	6064
F_2C_3	4883	6022	6389	5647	6016	5791
F_2C_4	4886	5843	6754	6643	5942	6014
F_2C_5	5053	5220	5196	5725	6073	5453
Mean	5741	5714	5732	5695	5868	5750

	S.Em ±	CD (0.05P)	CV (%)
F	29.55	82.91	
N	46.72	131.09	
C	29.55	82.91	
F x N	66.07	185.39	4.45
F x C	114.44	321.10	
N x C	104.47	293.12	
F x N x C	147.74	414.53	

Treatment details :

F_1 – Nano chemicals C_1 – Control C_4 – 750 ppm
F_2 –Bulk chemicals C_2 – 250 ppm C_5 – 1000 ppm
C_3 – 500 ppm

activities through rapid absorption of water and improved the germination (Banerjee *et al*., 2016). Hussain *et al.* (2019) reported that wheat seeds treated with silicon nanoparticles shown rapid germination, accelerate water absorption and with increased accumulation of biomass. Ali *et al.* (2022) found that


SiO2 TiO2 ZnO FeO S
3a)
Seedling length (cm)
F1C1 F1C2 F1C3 F1C4 F1C5 F2C1 F2C2 F2C3 F2C4 F2C5
Treatments
SiO2 TiO2 ZnO FeO S
3b)
Seedling dry weight (mg)
F1C1 F1C2 F1C3 F1C4 F1C5 F2C1 F2C2 F2C3 F2C4 F2C5
Treatments
SiO2 TiO2 ZnO FeO S
3c)
Seedling vigour index - I
F1C1 F1C2 F1C3 F1C4 F1C5 F2C1 F2C2 F2C3 F2C4 F2C5
Treatments

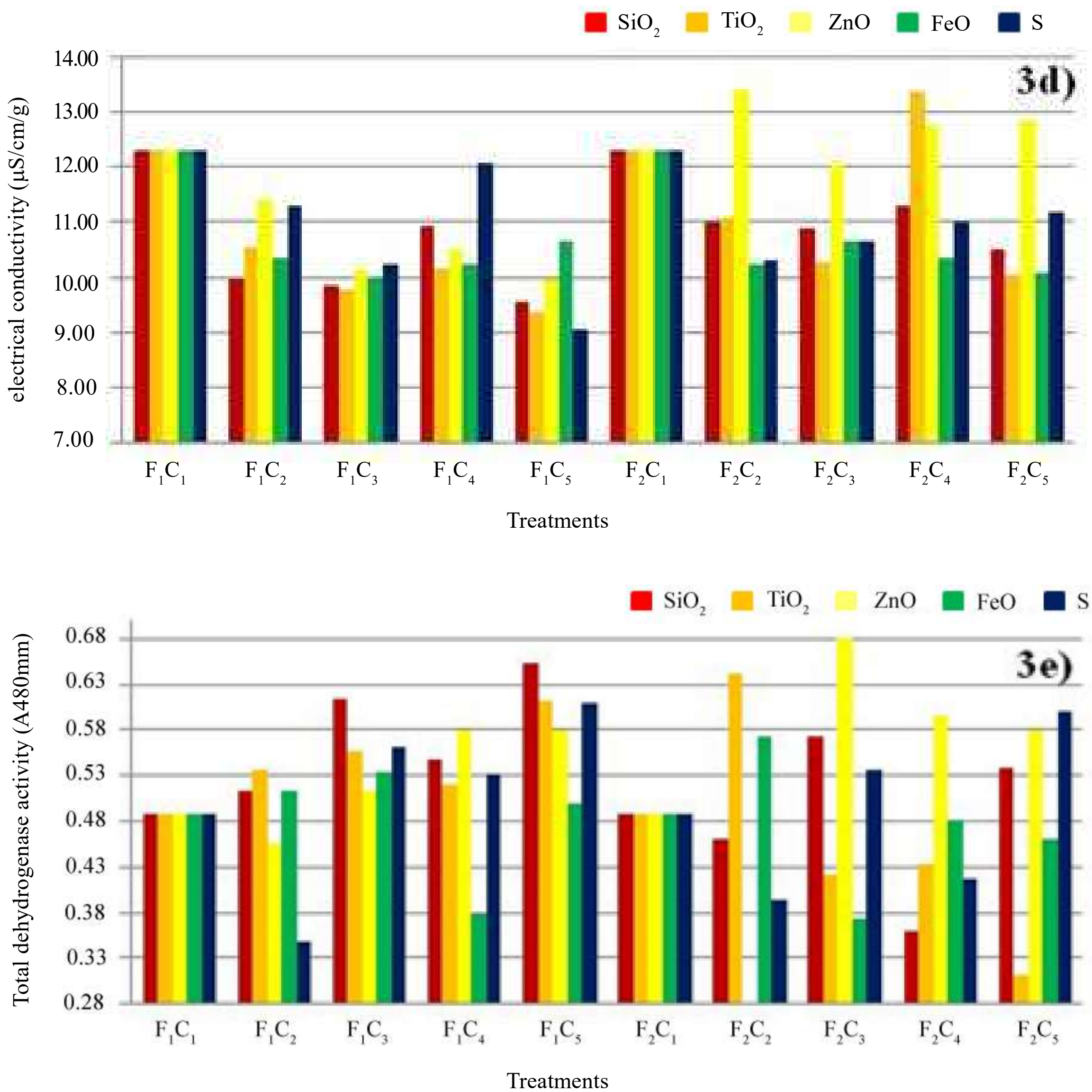


Fig. 3. Seed quality parameters (a to e) as influenced by dry dressing method of both nano and bulk form of chemicals in maize hybrid (MAH 14-138).

Treatment details :

F_1- Nano form; F_2-Bulk form; C_1- Control; C_2- 250mg; C_3- 500mg; C_4- 750mg; C_5- 1000mg

nano Ferric oxide increased plant height, number of leaves, root length, intermodal length and water absorption rate in wheat. ZnO NPs increased the chlorophyll content and enhanced antioxidant enzymes in drought amelioration (Itroutwar *et al.*, 2020). Further more, nanoparticles increased the activity of hydrolytic enzymes during germination and it involves in mobilization of food reserves effectively to facilitate early emergence and development of seedlings. According to Liu *et al.* (2021) Titanium dioxide nanoparticles found to increase the activity of antioxidant enzymes such as peroxidase, catalase, superoxidase and also it protects the chloroplast from injurious effect of Reactive Oxygen Species (ROS) in medicinal plants. Silicon dioxides play an important role in improving plant growth and development, stress tolerance and targeted nutrient availability in rice (Afzal *et al.*, 2021). The

TABLE 3

Effect of polymer medicated seed treatment with selected nano and bulk form of chemicals on germination (%) in maize hybrid *cv.* MAH 14-138

Treatments	Chemicals (N) both nano and bulk form					
	SiO_2	TiO_2	ZnO	FeO	S	Mean
F_1	92	97	98	97	99	96.6
F_2	92	97	97	96	97	95.8
Mean	92.0	97.0	97.5	96.5	98.0	96.2
Concentration (C)						
C_1	92	92	92	92	92	92.0
C_2	97	96	97	98	98	97.2
C_3	97	99	97	98	98	97.8
C_4	97	98	96	97	96	96.8
C_5	98	98	96	99	98	97.8
Mean	96.2	96.6	95.6	96.8	96.4	96.3
Interaction (F x C)						
F_1C_1	92	92	92	92	92	92.0
F_1C_2	97	97	97	99	97	97.4
F_1C_3	98	99	98	99	98	98.4
F_1C_4	97	99	96	98	95	97.0
F_1C_5	99	99	97	100	99	98.8
F_2C_1	92	92	92	92	92	92.0
F_2C_2	97	96	97	98	98	97.2
F_2C_3	96	98	96	97	97	96.8
F_2C_4	97	96	95	96	97	96.2
F_2C_5	98	96	96	98	96	96.8
Mean	96.3	96.4	95.6	96.9	96.1	96.3

	S.Em ±	CD (0.05P)	CV (%)
F	0.16	0.46	
N	0.26	0.73	
C	0.16	0.46	
F x N	0.37	1.03	1.47
F x C	0.63	1.78	
N x C	0.58	1.62	
F x N x C	0.82	2.29	

Treatment details :

F_1 – Nano chemicals	C_1 – Control	C_4 – 750 ppm
F_2 –Bulk chemicals	C_2 – 250 ppm	C_5 – 1000 ppm
	C_3 – 500 ppm	

TABLE 4

Effect of polymer mediated seed treatment with selected nano and bulk form of chemicals on seedling vigour index-II in maize hybrid cv. MAH 14-138

Treatments	Chemicals (N) both nano and bulk form					
	SiO_2	TiO_2	ZnO	FeO	S	Mean
F_1	4316	6716	6806	6614	7072	6305
F_2	4316	6132	6656	6447	6376	5985
Mean	4316	6424	6731	6531	6724	6145
Concentration (C)						
C_1	4316	4316	4316	4316	4316	4316
C_2	6700	6141	6993	6265	6022	6424
C_3	7082	6516	7027	6973	6058	6731
C_4	6806	6130	6736	6623	6357	6531
C_5	7457	6639	6690	6478	6357	6724
Mean	6472	5948	6352	6131	5822	6145
Interaction (F x C)						
F_1C_1	4316	4316	4316	4316	4316	4316
F_1C_2	6992	6955	7280	6270	6083	6716
F_1C_3	7445	6374	6976	7189	6045	6806
F_1C_4	6796	6590	7008	6404	6272	6614
F_1C_5	7945	6822	7007	6810	6777	7072
F_2C_1	4316	4316	4316	4316	4316	4316
F_2C_2	6408	5326	6706	6260	5961	6132
F_2C_3	6719	6657	7078	6756	6071	6656
F_2C_4	6816	5670	6464	6841	6443	6447
F_2C_5	6970	6457	6372	6145	5936	6376
Mean	6472	5948	6352	6131	5822	6145

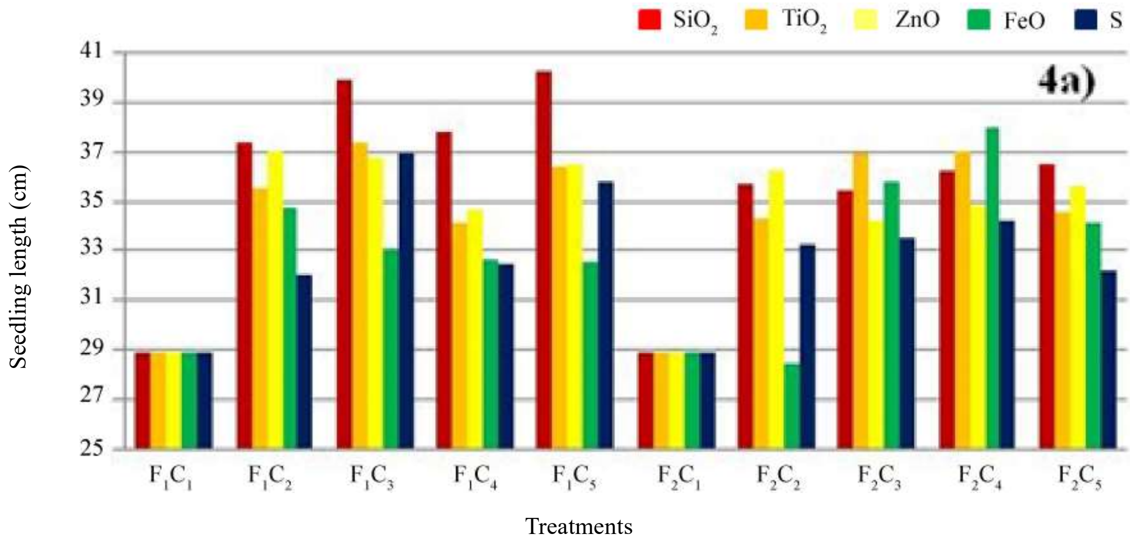
	S.Em ±	CD (0.05P)	CV (%)
F	35.04	92.32	
N	55.41	155.46	
C	35.04	98.32	
F x N	78.36	219.85	4.94
F x C	135.72	380.79	
N x C	123.89	347.61	
F x N x C	175.21	491.59	

Treatment details :

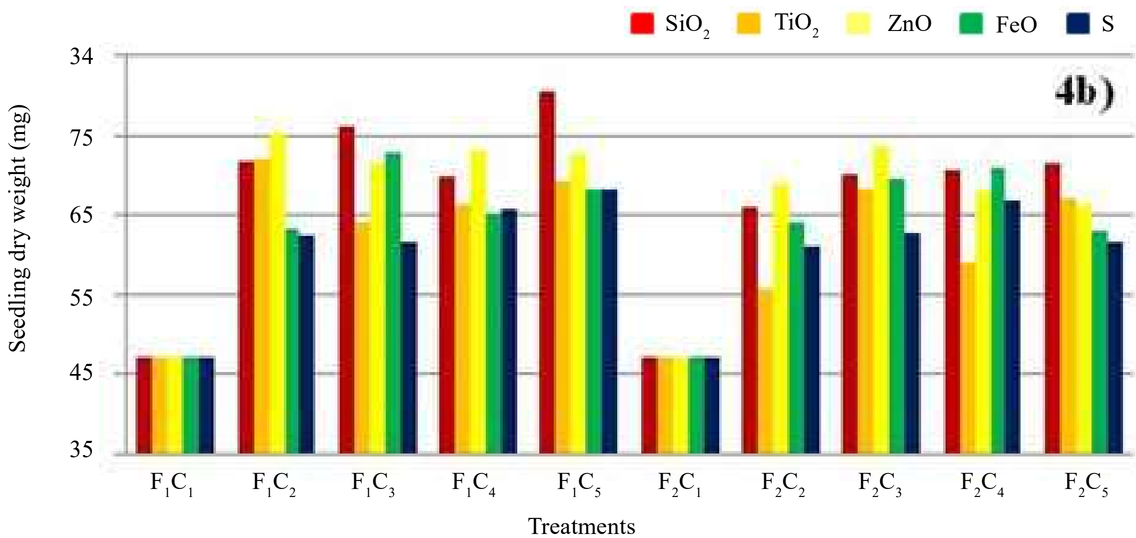
F_1 – Nano chemicals	C_1 – Control	C_4 – 750 ppm
F_2 –Bulk chemicals	C_2 – 250 ppm	C_5 – 1000 ppm
	C_3 – 500 ppm	

maize plant growth, yield and quality attributes are significantly increased by polymer film coating as seed protectants (Sumalata *et al*., 2017).

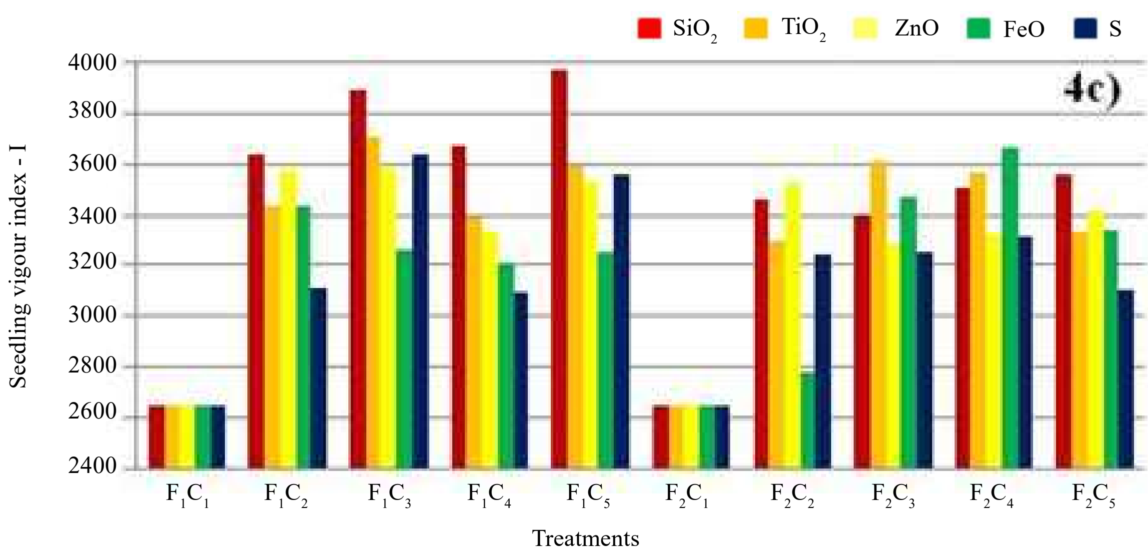
The seedling vigour index-I computed as the product of germination and seedling length was influenced by all the nanochemicals. Among those, maximum



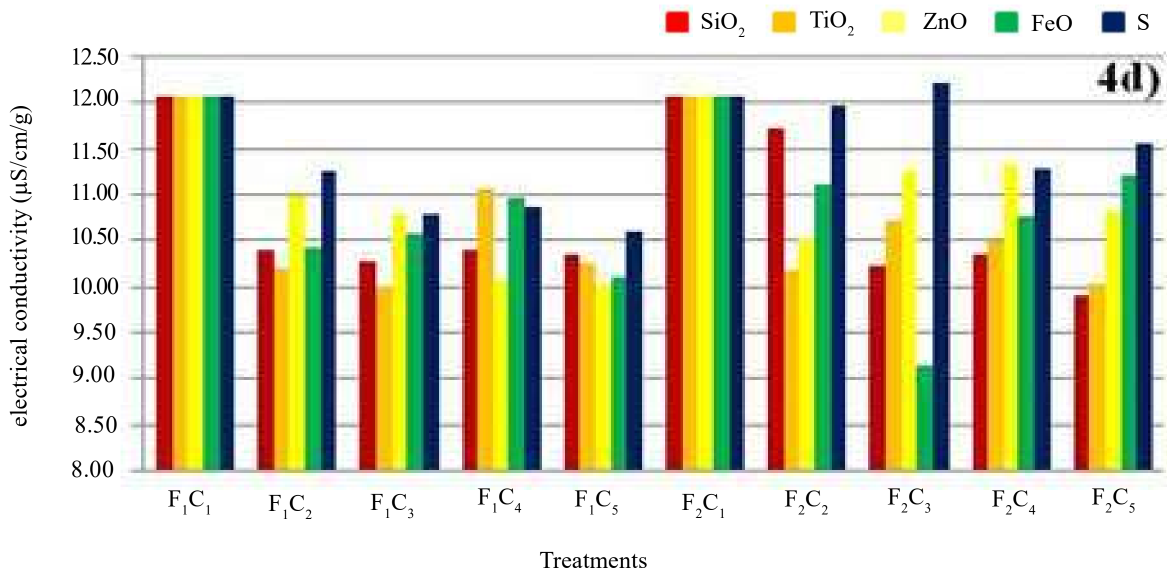
SiO_2 TiO_2 ZnO FeO S
4a)
Seedling length (cm)
41
39
37
35
33
31
29
27
25
F_1C_1 F_1C_2 F_1C_3 F_1C_4 F_1C_5 F_2C_1 F_2C_2 F_2C_3 F_2C_4 F_2C_5
Treatments



SiO_2 TiO_2 ZnO FeO S
4b)
Seedling dry weight (mg)
34
75
65
55
45
35
F_1C_1 F_1C_2 F_1C_3 F_1C_4 F_1C_5 F_2C_1 F_2C_2 F_2C_3 F_2C_4 F_2C_5
Treatments



SiO_2 TiO_2 ZnO FeO S
4c)
Seedling vigour index - I
4000
3800
3600
3400
3200
3000
2800
2600
2400
F_1C_1 F_1C_2 F_1C_3 F_1C_4 F_1C_5 F_2C_1 F_2C_2 F_2C_3 F_2C_4 F_2C_5
Treatments



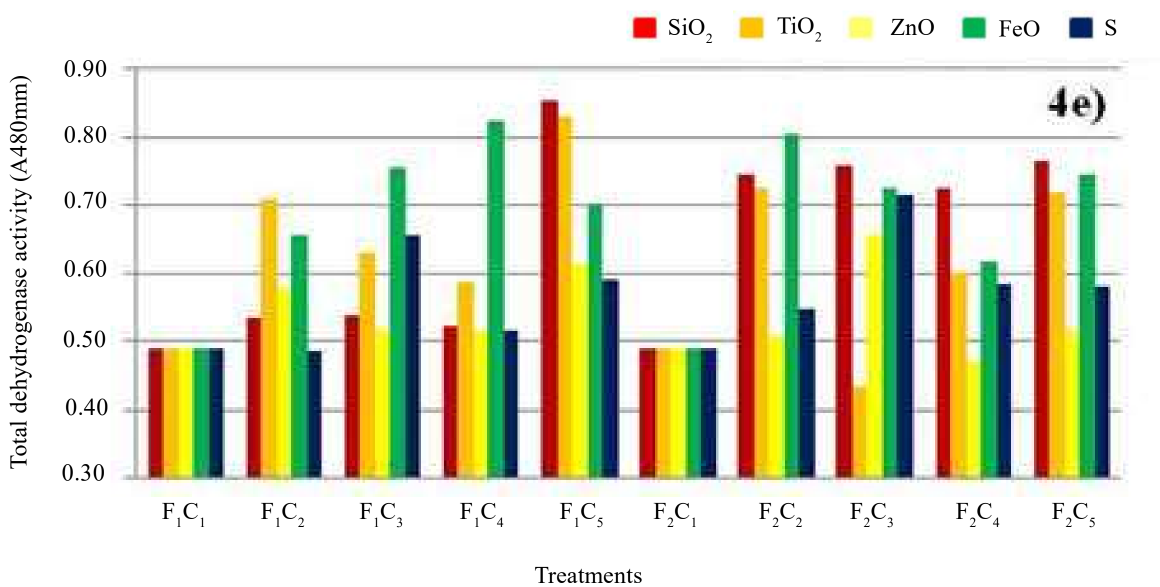


Fig. 4. Seed quality parameters (a to e) as influenced by polymer coating with both nano and bulk form of chemicals on maize hybrid (MAH 14-138).

Treatment details :

F_1- Nano form; F_2-Bulk form; C_1- Control; C_2- 250mg; C_3- 500mg; C_4- 750mg; C_5- 1000mg

seedling vigour (3968) was shown in polymer mediated coating with SiO_2 NPs @ 1000 mg/kg of seeds and it was on par with dry dressing of TiO_2 NPs @ 500 mg/kg of seeds (3948) whereas, it was lowest in wet soaking of SiO_2 NPs @ 1000 mg/kg (2919) and untreated control (2649). The data are depicted in Fig. 3c, 4c & 5c. Significantly, higher seedling vigour index-II (7945) (Tables. 2, 4 & 6) was recorded in polymer mediated coating with SiO_2 NPs @ 1000 mg/kg of seeds which was closely followed by dry dressing with ZnO NPs @ 1000 mg/kg of seeds (7810), but it was lowest in wet soaking of SiO_2 & ZnO NPs @ 1000 mg/kg (5798 and 5456, respectively), polymer coated seeds with bulk SiO_2

TABLE 5

Effect of wet soaking seed treatment with selected nano and bulk form of chemicals on germination (%) in maize hybrid cv. MAH 14-138

Treatments	Chemicals (N) both nano and bulk form					
	SiO_2	TiO_2	ZnO	FeO	S	Mean
F_1	95	97	97	96	96	96.2
F_2	95	95	95	96	95	95.2
Mean	95.0	96.0	96.0	96.0	95.5	95.7
Concentration (C)						
C_1	95	95	95	95	95	95.0
C_2	96	96	96	96	97	96.2
C_3	96	96	95	96	97	96.0
C_4	96	96	96	96	97	96.2
C_5	96	96	95	96	96	95.8
Mean	95.8	95.8	95.4	95.8	96.4	95.8
Interaction (F x C)						
F_1C_1	95	95	95	95	95	95.0
F_1C_2	97	96	96	97	97	96.6
F_1C_3	97	97	96	97	98	97.0
F_1C_4	96	96	97	96	97	96.4
F_1C_5	97	97	96	96	97	96.6
F_2C_1	95	95	95	95	95	95.0
F_2C_2	95	95	96	95	96	95.4
F_2C_3	96	95	95	95	96	95.4
F_2C_4	96	96	96	96	96	96.0
F_2C_5	95	95	95	95	95	95.0
Mean	95.9	95.7	95.7	95.7	96.2	95.8

	S.Em ±	CD (0.05P)	CV (%)
F	0.10	0.28	
N	0.16	0.45	
C	0.10	0.28	
F x N	0.23	1.63	0.91
F x C	0.39	1.10	
N x C	0.36	1.00	
F x N x C	0.51	1.42	

Treatment details :

F_1 – Nano chemicals C_1 – Control C_4 – 750 ppm
F_2 –Bulk chemicals C_2 – 250 ppm C_5 – 1000 ppm
C_3 – 500 ppm

TABLE 6

Effect of wet soaking seed treatment with selected nano and bulk form of chemicals on seedling vigour index-II in maize hybrid cv. MAH 14-138

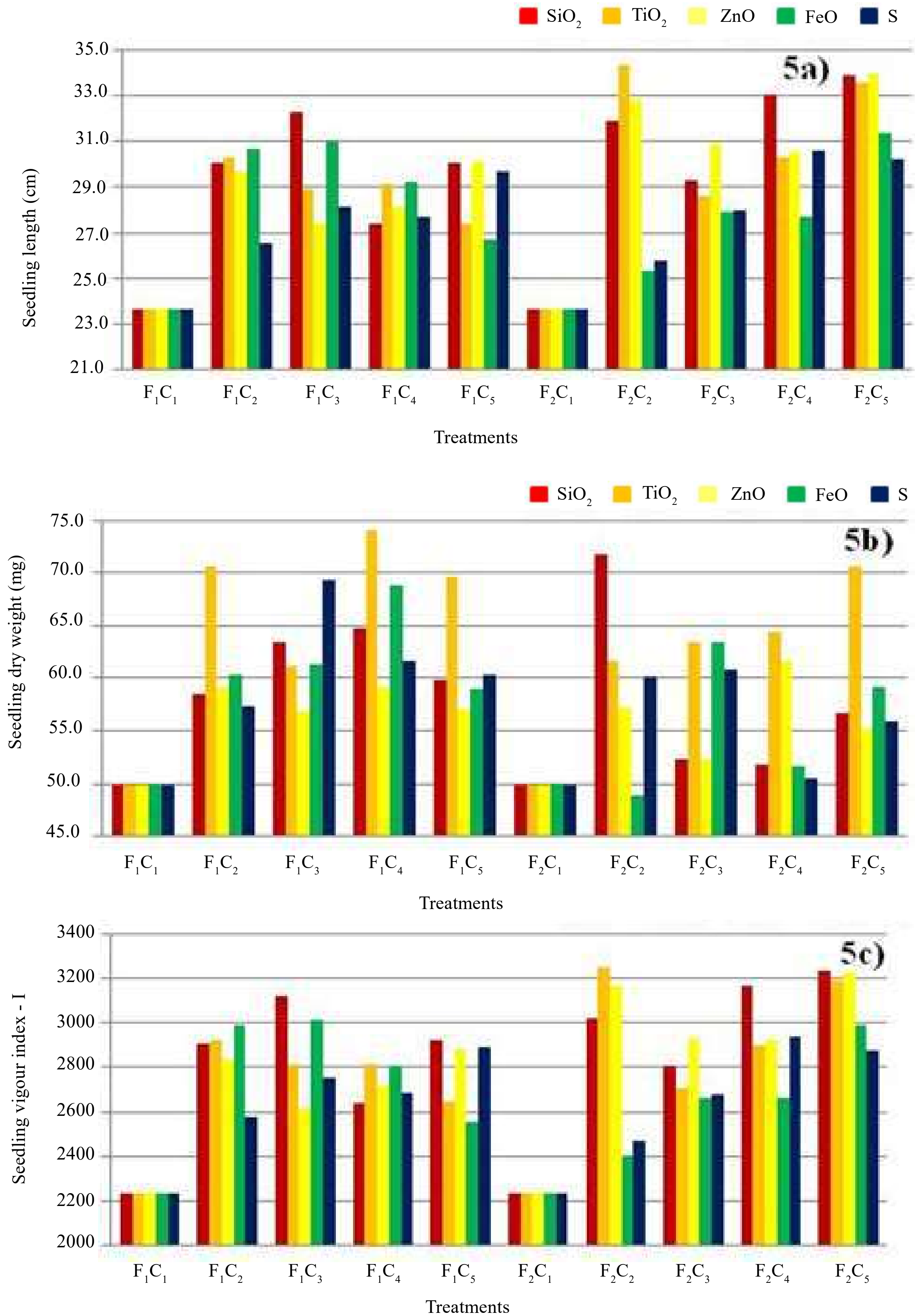
Treatments	Chemicals (N) both nano and bulk form					
	SiO_2	TiO_2	ZnO	FeO	S	Mean
F_1	4716	5914	6050	6335	5902	5783
F_2	4716	5703	5566	5365	5666	5403
Mean	4716	5809	5808	5850	5784	5593
Concentration (C)						
C_1	4716	4716	4716	4716	4716	4716
C_2	6222	6314	5585	5246	5678	5809
C_3	5571	5974	5196	6003	6295	5808
C_4	5609	6647	5804	5783	5408	5850
C_5	5599	6728	5348	5644	5602	5784
Mean	5543	6076	5330	5478	5540	5593
Interaction (F x C)						
F_1C_1	4716	4716	4716	4716	4716	4716
F_1C_2	5652	6800	5662	5872	5586	5914
F_1C_3	6131	5944	5436	5961	6776	6050
F_1C_4	6243	7132	5714	6614	5973	6335
F_1C_5	5798	6741	5456	5641	5872	5902
F_2C_1	4716	4716	4716	4716	4716	4716
F_2C_2	6792	5829	5507	4621	5770	5703
F_2C_3	5011	6004	4955	6045	5813	5566
F_2C_4	4976	6162	5894	4951	4842	5365
F_2C_5	5399	6714	5240	5646	5332	5666
Mean	5543	6076	5330	5478	5540	5593

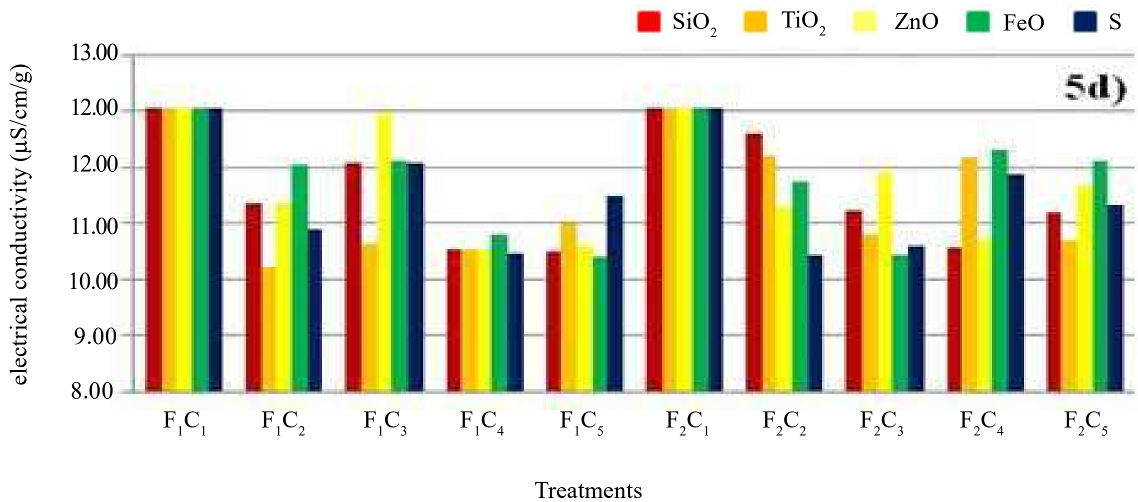
	S.Em ±	CD (0.05P)	CV (%)
F	27.10	76.02	
N	42.84	120.20	
C	27.10	76.02	
F x N	60.59	169.99	4.20
F x C	104.94	294.43	
N x C	95.80	268.78	
F x N x C	135.48	380.11	

Treatment details :

F_1 – Nano chemicals C_1 – Control C_4 – 750 ppm
F_2 –Bulk chemicals C_2 – 250 ppm C_5 – 1000 ppm
C_3 – 500 ppm

@ 1000 mg/kg (6970), dry dressing with bulk ZnO @ 1000 mg/kg of seeds (5196) and untreated control (4316). Similarly, Surabhi *et al*. (2018) reported that seedling vigour indices increased significantly due to SiO_2 NPs and ZnO NPs at different concentrations in pigeon pea. Faizan *et al.* (2021) also observed that


SiO2 TiO2 ZnO FeO S
5a)
Seedling length (cm)
35.0
33.0
31.0
29.0
27.0
25.0
23.0
21.0
F1C1 F1C2 F1C3 F1C4 F1C5 F2C1 F2C2 F2C3 F2C4 F2C5
Treatments
SiO2 TiO2 ZnO FeO S
5b)
Seedling dry weight (mg)
75.0
70.0
65.0
60.0
55.0
50.0
45.0
F1C1 F1C2 F1C3 F1C4 F1C5 F2C1 F2C2 F2C3 F2C4 F2C5
Treatments
5c)
Seedling vigour index - I
3400
3200
3000
2800
2600
2400
2200
2000
F1C1 F1C2 F1C3 F1C4 F1C5 F2C1 F2C2 F2C3 F2C4 F2C5
Treatments



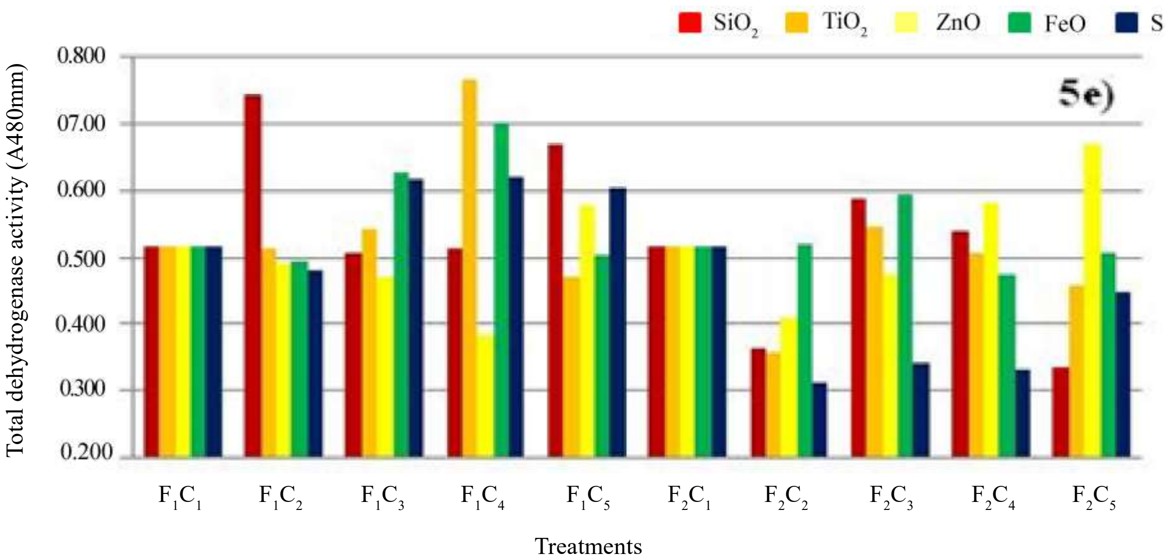


Fig. 5. Seed quality parameters (a to e) as influenced by wet soaking method of both nano and bulk form of chemicals on maize hybrid (MAH 14-138).

Treatment details :

F_1- Nano form; F_2-Bulk form; C_1- Control; C_2- 250mg; C_3- 500mg; C_4- 750mg; C_5- 1000mg

silicon nanoparticles decreased the translocation of roots, improved chlorophyll pigment production and activated rapid enzymatic activities in tomato. The improved activity of antioxidant enzymes indicated that functioning in ROS scavenging and restoration of plant growth and development under adverse conditions of soybean (Bhat *et al.*, 2022). SiO_2 nanoprimed stevia seeds were significantly improved the germination, root and shoot dry weight and seedling vigour compared to bulk as well as untreated control. It also increased the sucrose concentration, catalase (CAT) and peroxidase (POX) activity (Hasanaklou *et al.*, 2023).

The seed leachates constitutes electrolytes which was negatively associated with seed quality (Fig. 3d, 4d & 5d) was also lowest (9.36 µS/cm/g) in dry dressing with TiO_2 NPs @ 1000 mg/kg of seeds and dry dressing of SiO_2 NPs @ 1000 mg/kg of seeds

(9.54 µS/cm/g) when compared to bulk TiO_2 and SiO_2 @ 1000 mg/kg of seeds (10.05 and 10.48 µS/cm/g, respectively), wet soaking of TiO_2 NPs and SiO_2 NPs @ 1000 mg/kg (10.98 & 10.49 µS/cm/g, respectively) and untreated control (12.28 µS/cm/g). Nevertheless, the total dehydrogenase activity (TDA) was significantly higher (0.853) in polymer coated seeds with SiO_2 NPs @ 1000 mg/kg followed by polymer coated with TiO_2 NPs @ 1000 mg/kg (0.829) compared to polymer coated with bulk SiO_2 @ 1000 mg/kg (0.765) and wet soaking with SiO_2 NPs @ 1000 mg/kg (0.668) but they were superior over untreated control (0.487). The data pertaining to TDA are illustrated in Fig. 3e, 4e & 5e. The dry formulation of both SiO_2 and TiO_2 nanoparticles increased the respiration rate and mobilization of food reserves in maize seeds, chemical reactivity resulted in increase of synthesis and activity of dehydrogenase enzymes (Vijayalaxmi *et al*., 2013). Further, Surabhi *et al*., (2018) reported that nanoparticles at lower concentration protected the seed coat and thereby resulted in reduced leakage of solute or electrolytes from the seeds by maintaining the seed coat integrity. Silica nanoparticles could increase cell extension by formatting the complexes of silica polyphenol or lignin, which facilitate the cell wall loosening leads to increase the pigeon pea seed germination and also found that reduced relative electrolyte leachate (Korishettar *et al.,* 2016). Further, Rame Gowda *et al*. (2022) opined that nano priming stimulates the germination, establishment of plants, vigour, besides protecting plants against biotic and abiotic stresses, improved seed quality and productivity of crops. Besides, it also reduces the usage of commercial bulk form of chemicals, pesticides, fertilizers etc., in crop production.

The study revealed that seed treatment with nanochemicals found to be better over the conventional bulk form of chemicals in improving seed quality attributes in maize. Seed coating either with SiO_2 or TiO_2 nanochemicals @ 500 or 1000 mg/kg of seeds, with or without polymer mediated coating found effective over other seed treatments. Consequently, dry dressing of SiO_2 NPs @ 500 & 1000 mg/kg of seeds increased the germination by 8 per cent over the control and 12 per cent increase over its bulk form. Whereas, seedling vigour index-I increased by 33 per cent in polymer coated with SiO_2 NPs @ 1000 mg/kg over control and 10 per cent over its bulk form, while seedling vigour index-II increased by 46 per cent in polymer coated with SiO_2 NPs @ 1000 mg/kg over control and 12 per cent over bulk form. Therefore, seed polymer coating with SiO_2 nanochemical @ 500 mg/kg of seeds could be advocated cautiously to improve seed quality for subsequent crop performance in maize. Further, studies are also required to investigate the uptake of these chemical nutrients in nano form in order to find the causes for seed quality improvement.

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