

## Nano-anatase TiO<sub>2</sub> Modulates the Germination Behavior and Seedling Vigority of some Commercially Important Medicinal and Aromatic Plants

Mehrnaz Hatami\*, Mansour Ghorbanpour and Hossein Salehjarjomand

Department of Medicinal Plants, Faculty of Agriculture and Natural Resources, Arak University, Arak, IRAN

Received: 27.04.2014; Accepted: 11.05.2014; Published Online: 27.06.2014

### ABSTRACT

Nanoparticles have been applied worldwide, posing substantial effects on the environment and its living organisms. Plants as sessile organisms are always exposed to considerable fluctuations of nanoparticles concentrations. In this research, the influence of different concentrations (0, 10, 20, 40 and 80 mg.L<sup>-1</sup>) of nanosized TiO<sub>2</sub> were studied on seed germination parameters including germination percentage (GP %), mean time germination (MTG), germination rate (GR), germination index (GI) and seedling vigor index (SVI) of five different medicinal plant species namely *Salvia mirzayanii*, *Alyssum homolocarpum*, *Sinapis alba*, *Carum copticum*, *Nigella sativa*. Results indicated that significant differences in examined traits were found among the plant species and also among the employed TiO<sub>2</sub> concentrations. Among the plant species, the highest GR (87%) was observed in *S. alba* seeds at the 20 mg.L<sup>-1</sup> TiO<sub>2</sub> concentration, however, in *S. mirzayanii* plants it was obtained at 80 mg.L<sup>-1</sup> TiO<sub>2</sub>. The lowest MTG (1.55 day) was observed in *A. homolocarpum* seeds at 10 mg.L<sup>-1</sup> TiO<sub>2</sub> concentration. Moreover, the highest SVI (102.6) was observed in the 20 mg.L<sup>-1</sup> of the reference treatment for *S. alba* seeds. In *N. sativa* seeds, the highest GI value (9.29) was found at the anatase concentration of 20 mg.L<sup>-1</sup>. In conclusion, application of TiO<sub>2</sub> stimulated the seed germination of all species. However, this response was dependent on the concentration of applied TiO<sub>2</sub> and plant species as well.

**Key Words:** Nano TiO<sub>2</sub>, Anatase, Germination, Vigority, Medicinal Plants

### INTRODUCTION

Nanotechnology application is now widely distributed throughout life, and especially in agricultural systems. Nanoparticles, because of their physicochemical characteristics, are among the potential candidates for modulating the redox status and changing the seed germination, growth, performance, and quality of plants (Mukherjee and Mahapatra, 2009).

One of the main problems that prevent sustainable use of medicinal and aromatic plants, native to the arid lands is that they readily germinate within the native environment, but fail to show good germination under laboratory conditions or when cultivation is attempted (Gupta, 2003).

The ninth most abundant element and the second most abundant transition metal in the earth's crust is titanium element (about 6.32 ppm). The most important effects of Ti compounds on plants are enhancement of the yield of various crops (about 10–20%); an improvement of some essential element contents in plant tissues; an increase in the peroxidase, catalase, and nitrate reductase activities in plant tissues; and an enhancement of the chlorophyll content in paprika (*Capsicum anuum* L.) and green alga (*Chlorella pyrenoidosa*) (Hruby *et al.*, 2002). It has been reported that the germination rate and the germination and vigor indexes of spinach at 250–4,000 mg.L<sup>-1</sup> nanosized TiO<sub>2</sub> (<100 nm in diameter) treatments were improved in comparison with bulk-TiO<sub>2</sub> treatment (Zheng *et al.*, 2005). Lee *et al.* (2008) studied phytotoxicity and bioavailability of copper nanoparticles to the plants *Phaseolus radiatus* and *Triticum aestivum*, employing plant agar test as growth substrate. They concluded that the growth rates of both plants were constrained when exposure to nanoparticles and the seedling lengths were negatively related to the exposure concentration of nanoparticles. Contents of nanoparticles in plant tissues increased with increasing nanoparticle concentration in growth media; therefore, bioaccumulation was concentration dependent. Also, there is potential for expanding the range of TiO<sub>2</sub> nanoparticles use for improvement of physiological and morphological characteristics of crops (Mingyu *et al.*, 2007). However, some studies have reported negative effects of TiO<sub>2</sub> nanoparticles on higher plants that varied between plant tissues, growth stages, plant species, applied concentrations, and specific properties of nanoparticles (Castiglione *et al.*,

\* Corresponding author: hatamimehrnaz@yahoo.com

2011). Thus, the exploration of their extensive application in agriculture and plant science is still in debate (Kurepa *et al.*, 2010).

However, a few studies have been done on the effects of nanoparticles on medicinal and aromatic plants. In this work, we aimed to find out the phytotoxicity or positive effects of different concentrations of nanosized TiO<sub>2</sub> on seed germination parameters and seedling growth of some commercially important medicinal plants including *Salvia mirzayanii*, *Alyssum homolocarpum*, *Sinapis alba*, *Carum copticum*, *Nigella sativa*.

## MATERIALS AND METHODS

### *Plant materials*

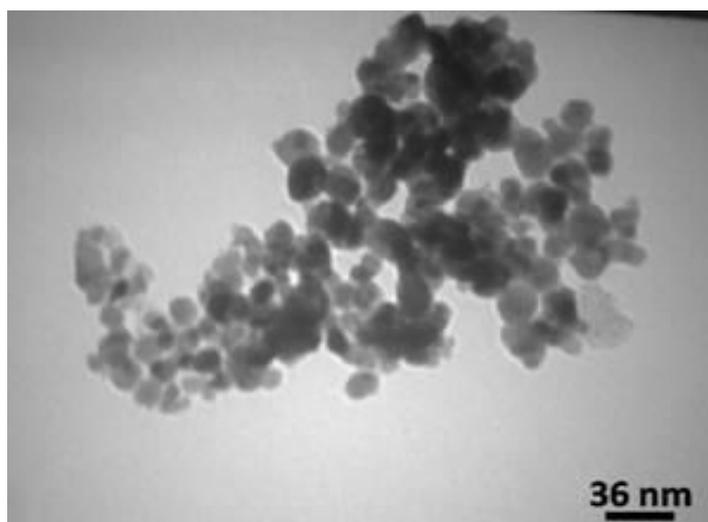
Seeds of five plant species from different families were used in this experiment (Table 1), as follows: *Salvia mirzayanii* Rech. f. & Esfand (Labiatae), *Alyssum homolocarpum* (Brassicaceae), *Sinapis alba* L. (Brassicaceae), *Carum copticum* L. (Umbelliferae), *Nigella sativa* (Ranunculaceae).

**Table 1.** Characteristics of different plant species and seeds tested in this experiment.

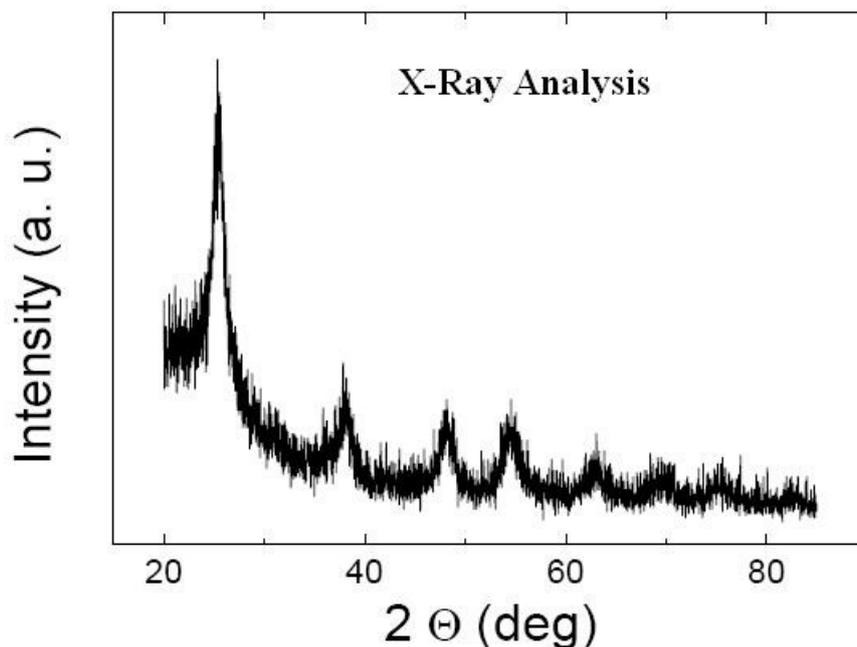
Species	Family	The part of the plant used	Seed 1000-weight (g)	Seed size (mm)	Seed color
<i>Salvia mirzayanii</i>	Labiatae	Seed	19	4	Grey
<i>Alyssum homolocarpum</i>	Brassicaceae	Seed	2	0.5	Yellow-Brown
<i>Sinapis alba</i>	Brassicaceae	Seed	6	2	Brown
<i>Carum copticum</i>	Umbelliferae	Seed	1.5	0.5	Grayish-Brown
<i>Nigella sativa</i>	Ranunculaceae	Seed	3	1	Black

### *Characterization of dioxide titanium (TiO<sub>2</sub>)*

TiO<sub>2</sub> nanoparticles were purchased from the Iranian Nanomaterials Pioneers Company, NANOSANY (Mashhad, Iran). The size of the TiO<sub>2</sub> nanoparticles was estimated to be 10-25 nm in diameter. A transmission electron microscopy (TEM) image of the TiO<sub>2</sub> particles is shown in figure 1. The crystal properties of TiO<sub>2</sub> nanoparticles were examined by X-ray diffraction (XRD). The XRD measurement showed that used TiO<sub>2</sub> nanoparticles were all present in the anatase form (Fig. 2). This form was considered to be more toxic than an equivalent sample of rutile TiO<sub>2</sub>. Characteristics of the TiO<sub>2</sub> used in current experiment were presented in table 2.



**Figure 1.** Transmission electron microscopy (TEM) image of TiO<sub>2</sub> nanoparticles. Distribution of particles size was estimated to be 10-15 nm (scale bar = 36 nm).



**Figure 2.** XRD pattern of TiO<sub>2</sub> nanoparticles. XRD measurement showed that used TiO<sub>2</sub> nanoparticles were in the anatase phase.

**Table 2.** Characteristics of nanosized TiO<sub>2</sub> used in current experiment.

Particel	Size (nm)	Purity (%)	Surface area (m <sup>2</sup> .g <sup>-1</sup> )	Color	Bulk density (g.cm <sup>-3</sup> )	True density (g.cm <sup>-3</sup> )	pH
Titanium Oxide Nanopowder (TiO <sub>2</sub> , anatase)	10-25	> 99%	200-240	white	0.24	3.9	6-6.5

### ***Seed preparation and treatment***

Seeds of the plant species were collected from their natural habitats in Markazy province, Iran, for testing the effects of various concentrations (0, 10, 20, 40 and 80 mg.L<sup>-1</sup>) of nanosized TiO<sub>2</sub> (anatase) on seed germination features including germination index (GI), germination percentage (GP), mean time germination (MTG), germination rate (GR) and seedling vigor index (SVI). After seed surface sterilization with sodium hypochlorite (1%, for 10 min) and rinse with sterilized water, they were placed on one layered Wathman No.1 filter paper moistened with 10 ml of employed solution in sterilized Petri dishes. Twenty seeds were selected for each treatment (in each plant species) and placed in Petri dishes and subsequently treated with reference solutions. In control, only distilled water in equal volume of anatase solution (10 ml) was used. After that, Petri dishes containing seeds were transferred to germinators with 16/8 h photoperiod, 20±2 °C temperature and relative humidity of 75%. The seeds were considered to be germinating at the moment of radicle emergence (1-2 mm in length). The number of germinated seeds was recorded daily and the final percentage of germination was measured after 10 days. The germination characteristics were calculated based on their formula. The experiment was carried out using three replicates per each treatment in a randomized completely design (RCD).

### **Germination indices measurement**

The final germination percentage (GP) was calculated based on total number of germinated seeds at the end of tenth day. The measurements were carried out according to International Rules for Seed Testing (ISTA, 1996). Germination indices as well as vigor index were calculated using the following equations (Alvarado *et al.*, 1987; Ruan *et al.*, 2002; Ellis and Roberts, 1981):

$$\text{Germination percentage (GP \%)} = (\text{Gf/n}) \times 100$$

Where, Gf is the total number of germinated seeds at the end of experiment and n is the total number of seed used in the test.

$$\text{Mean Time Germination (MTG)} = \sum \text{NiDi}/n$$

Where, Ni is number of germinated seeds till ith day and Di is number of days from start of experiment till i<sup>th</sup> counting and n is total germinated seeds.

$$\text{Germination rate (GR)} = \sum \text{Ni}/\sum \text{TiNi}$$

Where, Ni is the number of newly germinated seeds at the time of Ti.

$$\text{Germination Index (GI)} = \sum n/d$$

Where, n is the total germinated seeds at the time of d.

$$\text{Vigor index (VI)} = \text{SL} \times \text{GP\%}$$

Where, SL is seedling length at the end of test and GP% is the final germination percentage.

### **Statistical analysis**

Analysis of variance was performed on a randomized completely design (CRD) with 3 replications. The data were analyzed using SAS software (version 9.1; CoHort Software). The significant levels of difference for all measured traits were calculated, and the means compared by multiple range Duncan's test ( $P < 0.05$ ).

## **RESULTS AND DISCUSSION**

Significant ( $P < 0.05$ ) differences in examined traits were found among the five plant species and also among the employed TiO<sub>2</sub> concentrations (Table 3). In our current experiment, application of TiO<sub>2</sub> stimulated the seed germination of all species. However, this response was dependent on the concentration of applied TiO<sub>2</sub> and species as well.

In *Salvia mirzayanii* plants, results showed that the highest and the lowest GP (81% and 47%), were obtained in 80 mg.L<sup>-1</sup> concentration of nano-sized TiO<sub>2</sub> and control, respectively. However, the lowest MTG (2.55 day) was observed in the highest TiO<sub>2</sub> concentration. Also, the highest and the lowest GR (0.39 and 0.28 seed/day), SVI (46.62 and 12.3) were observed at 80 mg.L<sup>-1</sup> TiO<sub>2</sub> and control, respectively. Moreover, GI of the seeds was not significantly affected by treatments. Our findings possibly revealed the use of nano-TiO<sub>2</sub> (15-25 nm in diameter) increased the seed germination parameters of *S. mirzayanii* mucilage's seeds. Results of germination test on *Alyssum homolocarpum* plants indicated that the final GP was significantly affected by the employed treatment, however, increasing the concentration of nanosized dioxide titanium up to 40 caused an increase in seed germination and after that it declined. The lowest MTG (1.55 day) and the highest GR (0.62 seed/day) were obtained in 10 mg.L<sup>-1</sup> concentration of treatment. However, the maximum seedling SVI (14.27) was observed in the medium concentration (40 mg.L<sup>-1</sup>). However, in *Sinapis alba* plants the maximum GR (0.14 seed/day) with the lowest MTG (7.9 day) were obtained in 20 mg.L<sup>-1</sup> of TiO<sub>2</sub> concentration. Moreover, the highest (102.6) and the lowest (22) SVI were observed in the 20 and 80 mg.L<sup>-1</sup> of the reference treatment, respectively. However, variation of GI was not significantly ( $P < 0.05$ ) affected under all employed treatments. In our current study, nano-sized titanium oxide treatment especially in medium concentrations markedly improved

the *S. alba* seed germination parameters and seedling vigor index (GP× seedling length). For *Carum copticum* seeds, the highest (75%) and lowest (42.5%) germination percentage were obtained at 10 and 80 mg.L<sup>-1</sup> of TiO<sub>2</sub> concentration, respectively. Results also showed that the maximum GR (0.81 seed/day) and the lowest MTG (8.45 day) were obtained in 10 mg.L<sup>-1</sup> concentration of employed treatment. However, the lowest SVI (4.19) and GI (1.3) were observed in seeds treated with the highest TiO<sub>2</sub>. In our recent study, nano-sized titanium oxide treatment especially in low concentrations could markedly promote the *C. copticum* seed germination features and seedling vigor index. In *Nigella sativa* seeds, the lowest and the highest SVI (6.12 vs.9.29) were obtained in 20 mg.L<sup>-1</sup> concentration of nanoanatase and control treatments, respectively. However, the maximum (84.6%) and the minimum GP (68%) were observed in 20 and in control treatments, respectively. Also, the lowest MTG (6.43 day) were obtained in 20 mg.L<sup>-1</sup> of anatase concentration. Employing nanoanatase in appropriate concentration could promote the seed germination features and early growth of *N. sativa* in comparison to control. Generally, nanoparticles are materials that are small enough to fall within the nanometric range, with at least one of their dimensions being less than a few hundred nanometres. This reduction in size brings about significant changes in their physical properties with respect to those observed in bulk materials. Most of these changes are related to the appearance of quantum effects as the size decreases (Joseph and Morrison, 2006).

In a study with other type of nanomaterials, carbon nanotubes, results indicated that at the concentration range of 10-40 mg.L<sup>-1</sup> dramatically enhanced the seed germination and growth of tomato plants (Khodakovskaya *et al.*, 2009). The researchers hypothesized that the positive effect of nanomaterials arose from the capability of them to penetrate seed coat and therefore promote water uptake. Water uptake in seed germination is critical because mature seeds are relatively dry and need a substantial amount of water to initiate cellular metabolism and growth. The measured water moisture content of seeds and the detection of nanomaterials inside seeds supported the hypothesis; however, the specific penetration mechanisms through the coat and the enhancement of water uptake by nanomaterials were not reported. As a photocatalyst, nano-TiO<sub>2</sub> under light could cause an oxidation-reduction reaction (Crabtree, 1998).

**Table 3.** Seed germination responses and seedling vigor index variation of the five plant species, *S. mirzayanii*, *A. homolocarpum*, *S. alba*, *C. copticum*, *N. sativa*, under different nanosized TiO<sub>2</sub> concentrations.

Plant species	Treatment TiO <sub>2</sub> (mg.L <sup>-1</sup> )	Traits				
		GP (%)	MTG (day)	GR (seed/day)	SVI	GI
<i>Salvia mirzayanii</i>	0	47.0±1.2	4.58±0.3	0.28±0.01	12.30±0.1	5.26±0.9
	10	58.0±1.4	2.99±0.3	0.33±0.01	24.19±0.2	5.15±1.0
	20	68.0±1.9	2.85±0.2	0.36±0.02	34.43±0.3	5.53±0.8
	40	70.0±1.6	3.10±0.2	0.36±0.01	35.23±0.1	5.81±0.4
	80	81.0±2.1	2.55±0.1	0.39±0.03	46.62±0.1	6.08±0.5
	<b>LSD</b>		<b>1.64</b>	<b>0.22</b>	<b>0.016</b>	<b>0.15</b>
<i>Alyssum homolocarpum</i>	0	68.3±1.4	2.36±0.4	0.44±0.02	9.15±0.3	5.62±0.2
	10	76.6±1.2	1.55±0.1	0.62±0.03	11.94±0.2	5.84±0.3
	20	77.6±1.6	1.62±0.2	0.54±0.03	11.98±0.4	6.62±0.1
	40	83.3±2.3	1.89±0.1	0.55±0.02	14.27±0.1	7.36±0.2
	80	71.6±1.3	2.25±0.2	0.57±0.04	14.0±0.5	6.38±0.3
	<b>LSD</b>		<b>1.56</b>	<b>0.2</b>	<b>0.02</b>	<b>0.3</b>
<i>Sinapis alba</i>	0	71.3±2.3	8.10±0.2	0.11±0.05	45.0±1.5	5.47±0.2
	10	76.6±2.1	7.95±0.1	0.10±0.03	52.17±2.4	5.65±0.5
	20	87.0±2.5	7.90±0.4	0.14±0.02	102.67±5.7	5.68±0.4
	40	66.6±1.8	8.86±0.2	0.12±0.01	88.33±3.1	5.91±0.2
	80	48.3±1.5	9.46±0.2	0.10±0.03	22.0±1.8	5.71±0.2
	<b>LSD</b>		<b>2.04</b>	<b>0.22</b>	<b>0.02</b>	<b>2.9</b>
<i>Carum copticum</i>	0	65.0 ±1.4	9.64±1.5	0.52±0.04	13.70±1.3	2.64±0.4
	10	75.0±2.2	8.45±1.2	0.81±0.07	29.12±1.5	3.82±0.3
	20	72.9± 1.9	7.07± 1.1	0.64±0.02	24.34±1.2	3.65±0.3
	40	51.0±1.3	9.84±1.6	0.46±0.04	12.70±0.9	2.0±0.2

	80	42.5±1.1	9.91±1.4	0.41±0.01	4.19±0.3	1.3± 0.1
	<b>LSD</b>	<b>1.58</b>	<b>1.36</b>	<b>0.03</b>	<b>1.04</b>	<b>0.2</b>
<i>Nigella sativa</i>	0	68.0±1.5	8.47±0.9	0.72±0.03	22.73±0.3	6.12±0.2
	10	79.0±2.1	7.78±0.8	0.75±0.01	34.49±0.6	8.62±0.1
	20	84.6±2.2	6.43±0.5	0.83±0.04	53.20±0.2	9.29±0.6
	40	80.0±1.8	5.95±0.2	0.86±0.02	42.76±0.7	8.66±0.3
	80	70.0±1.3	9.46±1.1	0.77±0.01	23.45±0.1	6.21±0.2
	<b>LSD</b>	<b>1.78</b>	<b>0.7</b>	<b>0.021</b>	<b>0.38</b>	<b>0.3</b>

Abbreviations: GP, MTG, GR, SVI and GI refer to germination percentage, mean time to germination, seedling vigor index and germination index, respectively. Values represent mean ± standard deviation (SD), n=3.

Research showed that nano-TiO<sub>2</sub> treatment could markedly promote aged seeds' vigor and chlorophyll biosynthesis of spinach, particularly, the ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco) activity and the photosynthesis efficiency. The nano-TiO<sub>2</sub> treatment also has obvious effects on the improvement of growth and development in spinach. However, bulk TiO<sub>2</sub> treatment shows little effect (Zheng *et al.*, 2005).

Also, reported that a mixture of TiO<sub>2</sub> and SiO<sub>2</sub> nanoparticles at low concentrations increased nitrate reductase activity in the rhizosphere of soybean and consequently expedited soybean germination and growth (Lu *et al.*, 2002). According to Lin *et al.* (2004) nanoparticles SiO<sub>2</sub> enhanced the growth of Changbai larch (*Larix olgensis*) and the enhancement effect increased with concentration up to 500 mg.L<sup>-1</sup>. Moreover, it is suggested that Al<sub>2</sub>O<sub>3</sub> nanoparticles up to 4000 mg.L<sup>-1</sup> did not have any detectable effects on root elongation and development of Arabidopsis even though slight inhibition of seed germination was detected (Lee *et al.*, 2010). Metallic oxide nanoparticles such as ZnO were shown to be inhibitive at different developmental stages of plants such as seed germination and root elongation (Lin and Xing, 2007). Seed germination and root elongation are two standard indicators of phytotoxicity suggested by U.S. Environmental Protection Agency, yet several researches have indicated the insensitivity of seed germination for nanoparticles (Stampoulis *et al.*, 2009).

In our current work, different responses of the examined plant species to various nanosized TiO<sub>2</sub> dosages could be due to the following principal factors that previously reported by many researchers: concentration of nanoparticles, particle size and specific surface area, physicochemical properties of nanoparticles, plant species, plant age/life cycle stage, growth media conditions, nanoparticles stability, and dilution agent. The size of seeds could render more sensitivity to nanoparticles exposure. This is because a large seeded species (e.g., *S. mirzayanii*) has a lower surface to volume ratio than a small-seeded species (e.g., *S. alba*). However, a clear effect of the size of seeds on the toxicity of nanoparticles in plants cannot be confirmed at this time (Lee *et al.*, 2008; Lin and Xing, 2007). Lee *et al.* (2008) reported that mungbean was more sensitive than wheat to Cu nanoparticles toxicity, probably due to differences in root anatomy because xylem structures determine the speed of water transport and different xylem structures may demonstrate different uptake kinetics of nanoparticles. Mungbean is a dicot with one large primary root and several smaller lateral roots, whereas wheat is a monocot with numerous small roots without a primary root. However, generalization on whether the toxicity is based on dicot or monocot classification cannot be made. The concentration of nanoparticles is the major factor affecting toxicity in plants. The particle surface characteristic was also an important factor in nanoparticle toxicity (Yang and Watts, 2005). The works conducted in our laboratory also supported the more positive effects of nanosized TiO<sub>2</sub> than those of negative on seed germination parameters and vigority of tested medicinal plants particularly for mucilage's seeds.

In conclusion, here the seed germination and vigor index responses of five different medicinal plants, *Salvia mirzayanii*, *Alyssum homolocarpum*, *Sinapis alba*, *Carum copticum*, *Nigella sativa* were assessed with different concentration of TiO<sub>2</sub>. The results indicated that the nanosized TiO<sub>2</sub> treatments in appropriate concentrations accelerates the germination characteristics of the reference plant seeds and increases their vigor. We found that nanosized TiO<sub>2</sub> in medium concentrations (20-40 mg.L<sup>-1</sup>) has stimulatory effects on germination of most plants tested, except in *Salvia mirzayanii*, which the highest dosage (80 mg.L<sup>-1</sup>) was found to be more efficient for this mucilage's seeds plant.

## REFERENCES

- Alvarado, A.D., Bradford, K.J., Hewitt, J.D., (1987). Osmotic priming of tomato seeds, Effects on germination, field emergence, seedling growth and fruit yield. *J. Am. Soc. Hortic. Sci.* 112: 427-432.
- Castiglione, M.R., Giorgetti, L., Geri, C., Cremonini, R., (2011). The effects of nano-TiO<sub>2</sub> on seed germination, development and mitosis of root tip cells of *Vicia narbonensis* L. and *Zea mays* L. *J Nanopart Res.* 13: 2443–2449.
- Crabtree, R.H., (1998). A new type of hydrogen bond. *Science.* 282: 2000–2001.
- Ellis, R.A., Roberts, E.H., (1981). The quantification of ageing and survival in orthodox seeds. *Seed. Sci. Technol.* 9: 373-409.
- Gupta, V., (2003). Seed germination and dormancy breaking techniques for indigenous medicinal and aromatic plants. *Journal of Medicinal and Aromatic Plants Science.* 25, 402-407.
- Hruby, M., Cigler, P., Kuzel, S., (2002). Contribution to understanding the mechanism of titanium action in plant. *J Plant Nutr.* 25: 577–598.
- ISTA, (1996). International rules for seed testing. *Seed Science and Technology.* 13: 299-513.
- Joseph, T., Morrison, M., (2006). *Nanotechnology in Agriculture and Food.* Institute of Nanotechnology, Nanoforum Organization. Available:<http://www.nanoforum.org>
- Khodakovskaya, M., Dervishi, E., Mahmood, M., Xu, Y., Li, Z., Watanabe, F., (2009). Carbon nanotubes are able to penetrate plant seed coat and dramatically affect seed germination and plant growth. *ACS Nano.* 3: 3221–3227.
- Kurepa, J., Paunesku, T., Vogt, S., Arora, H., Rabatic, B.M., Lu, J.J., Wanzer, M.B., Woloschak, G.E., Smalle, J.A. (2010). Uptake and distribution of ultrasmall anatase TiO<sub>2</sub> alizarin red S nanoconjugates in *Arabidopsis thaliana*. *Nano Lett.* 10: 2296–2302.
- Lee, C.W., Mahendra, S., Zodrow, K., Li, D., Tsai, Y.C., Braam, J., Alvarez, P.j.j., (2010). Developmental phytotoxicity of metal oxide nanoparticles to *Arabidopsis thaliana*. *Environ Toxicol Chem.* 29: 669–75.
- Lee, W.M., An, Y.J., Yoon, H., Kwbon, H.S., (2008). Toxicity and bioavailability of copper nanoparticles to the terrestrial plants mung bean (*Phaseolus radiatus*) and wheat (*Triticum aestivum*): plant agar test for water-insoluble nanoparticles. *Environ Toxic Chem.* 27:1915-1921.
- Lin, D., Xing, B., (2007). Phytotoxicity of nanoparticles: inhibition of seed germination and root growth. *Environ. Pollut.* 150: 243–250.
- Lu, C.M., Zhang, C.Y., Wu, J.Q., Tao, M.X., (2002). Research of the effect of nanometer on germination and growth enhancement of *Glycine max* and its mechanism. *Soybean Sci* 21:168–172.
- Mingyu, S., Xiao, W., Chao, L., Chunxiang, Q., Xiaoqing, L., Liang, C., Hao, H., Fashui, H., (2007). Promotion of energy transfer and oxygen evolution in spinach photosystem II by nano-anatase TiO<sub>2</sub>. *Biol Trace Elem Res.* 119:183–192.
- Mukherjee, M., Mahapatra, A., (2009). Effect of coinage metal nanoparticles and zwitterionic surfactant on reduction of [Co(NH<sub>3</sub>)<sub>5</sub>Cl](NO<sub>3</sub>)<sub>2</sub> by iron(III). *Colloid Surface.* 350: 1-7.
- Ruan, S., Xue, Q., Tylkowska, K., (2002). The influence of priming on germination of rice *Oryzo sativa* L. seeds and seedling emergence and performance in flooded soil. *Seed. Sci. Technol.* 30: 61-67.
- Stampoulis, D., Sinha, S.K, White, J.C., (2009). Assay-dependent phytotoxicity of nanoparticles to plants. *Environ Sci Technol.* 43: 9473–9.
- Yang, L., Watts, D.J., (2005). Particle surface characteristics may play an important role in phytotoxicity of alumina nanoparticles. *Toxicol. Lett.* 158: 122–132.
- Zheng, L., Hong, F.S., Lu, S.P., Liu, C., (2005). Effect of nano-TiO<sub>2</sub> on strength of naturally aged seeds and growth of spinach. *Biol Trace Elem Res.* 104: 82–93.