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SPRING DURUM WHEAT (*TRITICUM DURUM* DESF. L.) RESPONSE TO IRON NANOPARTICLES DURING THE JUVENILE PERIOD OF DEVELOPMENT

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SUMMARY

Spring durum wheat (*Triticum durum* Desf. L.) is an important staple crop throughout the world, and its productivity enhancement can use the advanced nanotechnologies. Nanoparticles have become an environmentally safe fertilizer for grain crops. The presented work aimed to determine the effects of pre-sowing seed treatment with iron nanoparticles (Fe NPs) on the growth of six durum wheat cultivars (Milyana, Orenburgskaya-21, Bourbon, Bezenchukskaya Zolotistaya, Tselinnitsa, and Luch-25), as well as, assessing the toxicity of Fe NPs. The toxicity detection of nanoparticles employed the bacterial luminescence test system of *Escherichia coli* strain K12 TG1. For bioluminescence on a bacterial test model and assessing the effect of Fe NPs on plants, the experiment had the concentration range below 8×10^{-4} mg/ml. For each durum wheat cultivar, four experimental options included the control (seeds without treatment) and wheat seeds' treatment with four concentrations of Fe NPs (10^{-4}%, 10^{-5}%, 10^{-6}%, and 10^{-7}%). Afterward, the assessment of germination energy after five days and morphometric parameters of seedlings after seven days ensued.

Keywords: Spring durum wheat (*T. durum* Desf. L.), nanoparticles, Fe, pre-sowing treatment, toxicity, cultivar specificity, growth traits

Key findings: Spring durum wheat (*T. durum* Desf. L.) seed treatment with Fe NPs enhanced plants' shoot and root length and stimulated the seedling biomass accumulation. However, these effects depended on the metal concentration in the polymer composition and the wheat genotype.

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INTRODUCTION

In temperate countries, the agricultural sector's maintenance ensures increased grain production, with wheat being the main crop. However, the cereal grains' demand steadily rises due to population growth and increased livestock production. Increasing the spring durum wheat (*Triticum durum* Desf. L.) productivity can succeed with improved quality parameters, using innovative technologies to replace traditional farming methods. Recently, nanotechnology has shown as an emerging approach applicable in agriculture to improve crops' productivity using nanoparticles as seed treatments and foliar sprays on crop plants. In this regard, numerous studies are actively progressing to probe the influence of nanoparticles on various aspects of the agricultural system (Rabinovich and Lyubimova, 2021).

Heightened attention to nanotechnology and the unique properties of metals in nanoscale make use of nanoparticles (NPs) relevant in agriculture (Shah and Wu, 2019). The huge specific surface area of nanoparticles increases their ability to interact with living organisms, and their small size allows them to easily penetrate cell walls, enhancing cellular uptake and structural modification in the plant's body (Shang *et al.*, 2019). The metal nanoparticles have low toxicity and 7–50 times less than the toxicity of metals in ionic form. Moreover, these NPs have a prolonged and multifunctional effect and stimulate metabolic processes in crop plants (Yurina *et al.*, 2021).

The drug's use as nanoparticles for plant protection and nutrition optimization focuses on augmenting productivity, as well as, reducing the load of different conservational factors on the environment. Unlike traditional ones, by using fertilizers with nanoparticles, the release of nutrients into the soil occurs gradually. This eventually leads to an increased efficiency of the elements and a reduction in the frequency of fertilization, decreasing soil pollution and the negative effects caused by their excessive consumption (Sekhon, 2014).

The strategy of using NPs to provide microelement nutrition to crop plants has become the pre-sowing of seed treatment, with little nutrient consumption in the initial period of plant life. However, the lack of any element significantly impairs their growth and development, which negatively affects crop productivity. Subsequently, the sufficient provision of crop plants with this element cannot completely fix the situation (Goman *et al.*, 2020; Zhang *et al.*, 2023). Pre-sowing seed treatment has proven effective in boosting the germination and activating various physiological processes of plants, making them more resistant to numerous abiotic and biotic stresses in the field.

Nanoparticles based on Zn, Cu, Ag, Mn, and their oxides are the most used in field practice of crop plants (Elsharkawy and Derbalah, 2019). Their influence on the morphological parameters and productivity of various crops has gained validation (Singh *et al.*, 2021). However, their effect in the context of cultivars of the same crop has limited studies. Therefore, the routine use of any nanomaterial in the agricultural industry requires an individual study about its effect on crop plants (Anokhina *et al.*, 2017).

The presented study showed for the first time the pre-sowing seed treatment with iron nanoparticles on certain physicochemical properties affects the morphological parameters of spring durum wheat. Although, in this case, the crop effects depended upon the used concentration of the metal in the polymer composition and the genotype. The purpose of the latest research was to study the effects of iron nanoparticles on bacterial luminescence and morphometric parameters of seedlings of different spring durum wheat cultivars with pre-sowing Fe NPs seed treatment.

MATERIALS AND METHODS

Plant material

The study object was the six cultivars of *Triticum durum* Desf. (Milyana, Orenburgskaya-21, Bourbon, Bezenchukskaya Zolotistaya, Tselinnitsa, and Luch-25). From the 2023 harvest, the seeds of various

Table 1. Characteristics of plant materials used in the study.

Cultivars	Weight					G (%)	Cultivation region
	N (%)	p (%)	r (%)	K (mg/kg)	P (%)		
Bezenchukskaya Zolotistaya	1.71	7.75	1.72	2670.0	0.05	23	7, 8, 9
Luch-25	1.31	7.47	1.72	2790.0	0.07	17	7, 8
Milyana	1.75	9.98	2.06	2820.0	0.09	32	9
Tselinnitsa	0.64	9.35	1.64	2820.0	0.05	30	9
Bourbon	1.68	9.58	1.80	3220.0	0.06	31	9
Orenburgskaya-21	1.58	9.01	1.88	2770.0	0.08	28	9

Note: N = nitrogen, p = protein, r = raw ash, K = potassium, P = phosphorus, and G = gluten; numbers indicate regions of Russia: 7 = Middle Volga, 8 = Lower Volga, 9 = Ural.

cultivars came from the breeding and seed production center of the Federal Scientific Center BST RAS, Orenburg, Russia. The biochemical composition of grains and the regions appear in Table 1.

Nanoparticles

Obtaining iron nanoparticles by high-temperature condensation used the Migen-3 installation (Gen and Miller, 1981; Leipunsky *et al.*, 2019). The study of physicochemical properties proceeded at the Laboratory of Nano- and Micro-structural Materials Science of the Institute of Energy Problems of Chemical Physics RAS, Moscow, Russia. In the nanoparticle characteristics, the average diameter of Fe NPs was 27.0 ± 0.51 nm, the crystalline metal phase was 53.6% ± 4.2%, the iron oxide phase was 46.4%, the thickness of the oxide film was 3.5 nm, and zeta potential was 12.8±0.1 mV.

Research methodology

Before starting of the experiment, the seeds sustained surface sterilization in a 2% chlorine solution for 5 min and washing several times with distilled water, completely removing traces of the disinfectant solution. For seed germination, sterilizing the filter papers and vessels at 130 °C took one hour. Suspension preparation of iron NPs with four different concentrations (10^{-4}%, 10^{-5}%, 10^{-6}%, and 10^{-7}%) progressed by dispersing an accurately weighed portion of powders in distilled water on an ultrasonic disintegrator UP50H (Hielscher, Germany), at 3 × 30 seconds (0.5 A, 44 kHz) while cooling. The finished suspension of powders' dispersion into a polymer composition of Na-carboxymethyl cellulose (Na-CMC) and polyethylene glycol 400 (PEG-400) received a solution of Na-EDTA at a concentration of 0.00037% and dispersed again. Seeds treatment with the finished preparation had the rate of 5 ml per 100–150 pieces. Seeds of the control group received distilled water only. Seed germination continued in rolls in a thermostat at a temperature of 20 °C ± 1 °C, according to GOST 12038-84 (2011). On the third day, the germination energy assessment ensued. On the seventh day, the observations proceeded on the following parameters, i.e., seed germination, seedling length, the number and length of embryonic roots, and the weight of roots and seedlings.

The toxicity determination of Fe NPs used the luminescent bacterial strain *Escherichia coli K12 TG1*, carrying a hybrid plasmid with the structural bioluminescence genes of *Photobacterium leiognathi*, according to the manufacturer's recommendations (Ecolum, NVO Immunotech, Russia). Recording the level of inhibition of bacterial luminescence employed a multifunctional microplate reader, TECAN Infinite F200 (Tecan Austria GmbH, Austria) for three hours. Adding the test samples to the wells of the bacterial suspension had a ratio of 1:1. Toxicological parameters EC_{20} and EC_{50}, calculated at 60, 120, and 180 min of contact, served as integral characteristics of the recorded biological activity. Control samples with distilled water added to the cells helped record the background glow of bacteria. The criterion for assessing biological activity was the change in the intensity of bioluminescence of the test object in the analyzed sample compared with the control sample, excluding toxic agents (Deryabin *et al.*, 2016).

Statistical analysis

The compilation of the obtained triplicate data continued using standard methods of variation statistics in Microsoft Excel 2010 and Statistica 12 (StatSoft, Inc. USA). The average values of the studied indicators (M) and standard errors of the mean (± SEM) were successful. The parametric independent groups' Student's t-test helped assess the significance. Differences between variants were notably significant at $P \leq 0.05$. Detecting the influence of factors on the variability of the studied parameters utilized the two-factor analysis of variance.

RESULTS AND DISCUSSION

The biological activity of iron NPs analysis used the glow pattern of luminescent bacteria. The analysis established iron in ultradisperse form in the concentration range of 12.5 mg/ml and above exhibited the highest biological activity with complete quenching of the biosensor and indicating the death of bacterial target cells (Table 2). The overall dynamics of the luminosity of the bacterial strain showed an increase in relative luminescence with decreased concentration of Fe NPs in the medium.

The semi-lethal concentration (EC_{50}) and the concentration causing the death of 20% of bacteria (EC_{20}) at 180 min were at the level of 2.4×10^{-2} and 3×10^{-3} mg/ml, respectively. However, the dilution of the concentration (1.5×10^{-3} mg/ml) contributed to a decrease in luminescence once contact began. The indicators corresponded to the EC_{20} threshold criterion; however, after 30 min of exposure gave an undetectable effect. At 180 min, the said concentration was characteristically non-toxic. The introduction of iron NPs into the medium with a concentration of 8×10^{-4} mg/ml and lower give a non-inhibitory effect on the luminescence parameters. Thus, the safe use of Fe NPs on a biological object was permissible at a concentration of 8×10^{-4} mg/ml. Hence, the use of Fe NPs in pre-sowing seed treatment was better with the concentration range of 8×10^{-4} mg/ml and below.

The seedling vigor and number of seedlings are supposedly the most important traits determining the future harvest, and the influence of NPs with different concentrations on variations in the germination capacity and germination energy of durum wheat seeds.

Table 2. Relative value of luminescence of a bacterial strain in an environment with different contents of Fe NPs.

Time (min)S	Concentration of Fe NPs (mg/ml)									
	12.5	6.25	19.5 $\times10^{-2}$	9.8 $\times10^{-2}$	4.9 $\times10^{-2}$	2.4 $\times10^{-2}$	1.2 $\times10^{-3}$	3.1 $\times10^{-3}$	1.5 $\times10^{-3}$	8 $\times10^{-4}$
0	4.17	5.81	11.07	17.93	37.89	47.49	59.71	71.34	79.10	80.18
30	2.11	3.87	12.07	16.08	39.07	39.69	49.14	74.21	81.83	80.87
60	1.60	3.31	13.72	18.53	46.79	45.16	56.01	74.67	85.14	80.06
90	1.89	4.09	19.11	26.60	50.57	59.32	73.47	76.20	86.29	82.39
120	3.06	6.38	20.29	28.35	53.62	56.32	72.24	77.79	86.57	83.74
150	4.27	8.43	16.66	24.12	57.54	55.11	72.23	79.16	86.04	84.51
180	5.44	9.92	15.84	22.64	60.39	53.90	70.92	79.77	84.77	84.79

Note: The numerical values correspond to the relative value of luminescence (%), the color shading corresponds to the threshold values, which are, concentrations of NPs that cause over 95%, 80%, 50%, and 20% of the biosensor quenching and are non-toxic doses, respectively.

– Tox, – EC_{80}, – EC_{50}, – EC_{20}, – NTOX,

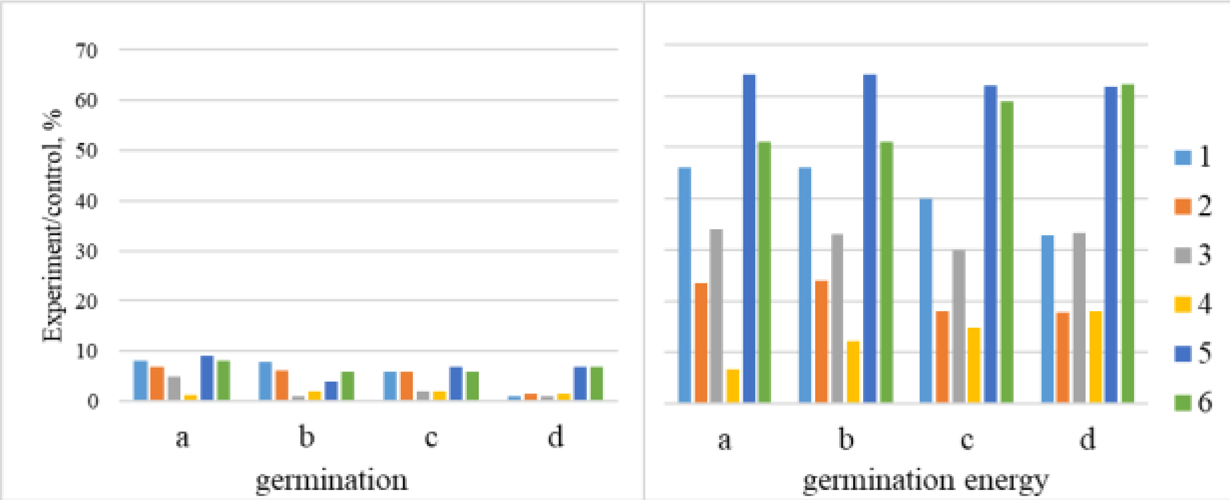

Figure 1. The effect of Fe NPs introduced into the polymer composition at concentrations of 10-4% (a), 10-5% (b), 10-6% (c), and 10-7% (d) on the germination energy and germination of durum wheat seeds Tselinnitsa (1), Orenburgskaya-21 (2), Milyana (3), Bourbon (4), Bezenchukskaya Zolotistaya (5), and Luch-25 (6).

However, the results largely depended on the durum wheat cultivars. If one takes seed germination in the control to be 100%, then the effect of metal NPs on germination energy was considerably ($P \leq 0.05$) more, ranging from 113% (cultivar Bourbon) to 163% (cultivar Bezechukskaya Zolotistaya) (Figure 1).

The greatest effect of increasing the germination energy was visible in the cultivars Bezenchukskaya Zolotistaya and Luch-25, with 63% and 56.1% more than the control treatment. By treating the durum wheat seed with Fe NPs, on average, the germination percentage increased by 2%–9% in the presented experiment. However, the variations were minor, since the seeds initially had the high germination rates. On NPs concentrations, in germination rate, the maximum increase was evident at the iron NPs with polymer film (10^{-4}%). In general, the assessment of germination energy and seed germination of the studied durum wheat cultivars revealed a positive effect of pre-sowing seed treatment with Fe NPs in the composition of polymers. Wohlmuth *et al*. (2022) reported the perfect effects of various nanoparticles on the seed germination process of different crops.

Pre-sowing seed treatment significantly affected the morphological parameters of the spring durum wheat seedlings, causing both stimulation and inhibition of growth processes (Table 3). In the control variant, the average length of the sprout varied from 5.5 ± 0.3 cm (cultivar Bezenchukskaya Zolotistaya) to 9.1 ± 0.4 cm (cultivar Luch-25). By treating with the iron nanoparticles, the length of the sprout showed a significant ($P \leq 0.05$) increase by 15.3% to 20.6%, with the highest values recorded for the cultivar Tselinnitsa and the lowest in Luch-25. In the process of studying the effect of low-frequency metals, some studies reported the manifestation of species specificity in the shoots' response of various crops (Ermokhin and Bobrenko, 2003; Ryabinina *et al.*, 2023).

Pre-sowing treatment of seeds with Fe NPs increased the average root length of all the durum wheat cultivars. On average, a reliable ($P \leq 0.05$) increase in this trait relative to control samples was 8.3% to 16.2%. However, by treating with Fe NPs concentration of 10^{-4}%, the highest root length appeared in the cultivars Tselinnitsa (7.6 cm), Milyana (9.0 cm), and Bourbon (7.2 cm). Similar results occurred in cultivars Bezenchukskaya

Table 3. The influence of pre-sowing seed treatment with iron nanoparticles on the morphological characteristics of durum wheat seedlings.

Fe NPs concentration (%)	Sprout length (cm)	Average spine length (cm)	Total length of the root system (cm)	Dry weight of the sprout (10^{-3} g)	Dry weight of the root system (10^{-3} g)
Tselinnitsa					
without processing	6.3±0.3	6.3±0.6	29.9±1.8	4.7±0.5	4.4±0.1
10^{-4}	7.3±0.2	7.6±0.3*	35.7±1.3*	5.9±0.2*	5.5±0.4*
10^{-5}	7.6±0.3	7.1±0.2*	33.4±1.3	5.5±0.6*	4.5±0.2
10^{-6}	7.0±0.2	7.5±0.3*	34.9±1.4	5.2±0.8	4.9±0.3
10^{-7}	6.2±0.4	6.4±0.2	30.7±1.6	4.7±0.4	4.5±0.1
Orenburgskaya-21					
without processing	8.3±0.4	8.0±0.3	38.3±1.3	6.0±0.5	5.1±0.6
10^{-4}	9.6±0.3	8.7±0.2*	42.4±2.1*	7.3±0.4*	5.8±0.2*
10^{-5}	8.8±0.5	8.8±0.1*	41.6±1.6*	6.4±0.3*	5.5±0.1
10^{-6}	8.5±0.2	8.1±0.3	40.0±1.2	6.3±0.3	5.2±0.5
10^{-7}	8.2±0.2	7.9±0.1	39.1±1.1	5.9±0.2	4.9±0.8
Milyana					
without processing	8.5±0.4	8.1±0.3	38.1±1.4	6.4±0.3	5.3±0.3
10^{-4}	9.2±0.6	9.0±0.4*	41.4±1.1*	7.2±0.2*	5.8±0.3*
10^{-5}	8.7±0.2	8.3±0.2	39.0±1.2	6.6±0.4	5.7±0.4
10^{-6}	8.8±0.3	8.4±0.4*	40.6±2.2	6.6±0.2	5.7±0.6
10^{-7}	8.6±0.2	8.3±0.2	38.8±1.3	6.7±0.3	5.5±0.5
Bezenchukskaya Zolotistaya					
without processing	5.5±0.3	5.7±0.3	28.0±1.1	4.5±0.2	4.5±0.1
10^{-4}	5.8±0.5	6.0±0.1	27.8±1.4	4.5±0.1	4.4±0.1
10^{-5}	6.1±0.4	5.9±0.2	28.1±2.2	5.3±0.3*	5.2±0.2
10^{-6}	5.2±0.3	6.6±0.4*	30.6±1.3	4.4±0.2	4.9±0.1*
10^{-7}	6.6±0.4	7.4±0.6*	32.6±1.1*	5.6±0.2*	5.6±0.2*
Bourbon					
without processing	8.3±0.5	6.2±0.2	32.0±2.1	5.6±0.4	5.0±0.5
10^{-4}	9.4±0.2	7.2±0.3*	34.2±1.6*	6.8±0.3*	5.6±0.2*
10^{-5}	8.9±0.6	6.5±0.1	33.8±1.2	6.0±0.2	5.1±0.6
10^{-6}	9.0±0.4	6.5±0.2	33.6±1.5	6.0±0.4	5.1±0.5
10^{-7}	8.2±0.3	6.3±0.3	31.7±1.1	5.7±0.2	5.0±0.2
Luch-25					
without processing	9.1±0.4	6.7±0.1	33.4±1.4	5.6±0.4	5.1±0.2
10^{-4}	8.5±0.5	5.9±0.4*	29.9±1.3*	5.5±0.2	4.8±0.6
10^{-5}	9.2±0.3	7.1±0.2	35.5±1.3	5.6±0.3	5.3±0.4*
10^{-6}	9.4±0.2	7.2±0.3	36.7±1.8	5.7±0.1	5.1±0.2
10^{-7}	9.9±0.3	7.5±0.1*	38.2±1.5*	6.2±0.1*	5.4±0.2*

Note: Data are presented as average M±SEM. * Differences between variants were considered statistically significant at $P \leq 0.05$.

Zolotistaya (7.4 cm) and Luch-25 (7.5 cm) at the Fe NPs concentration of 10^{-7}%, and durum wheat genotype Orenburgskaya-21 (8.8 cm) at the Fe NPs concentration of 10^{-5}%. The results also exhibited in the cultivar Luch-25, the iron nanoparticles into the polymer film (10^{-4}%) significantly ($P \leq 0.05$) reduced the root length versus the control.

For the root system's total length, the analysis of variability revealed most NPs treatments showed a remarkable increase in root system relative to the control. However, the durum wheat cultivars displayed substantial differences in root system. The highest length of the root system was evident in the cultivars Orenburgskaya-21 (42.4 cm), Milyana (41.4 cm), Bourbon (34.2 cm), and Tselinnitsa (35.7 cm), by treating with Fe NPs concentration (10^{-4}%). It significantly ($P \leq 0.05$) exceeded the control values for the said genotypes (9.4%, 9.0%, 6.9% and 19.4%, respectively). However, in the polymer composition, the reduced metal concentration also lessened the said effect.

In contrast, in durum wheat cultivars Bezenchukskaya Zolotistaya and Luch-25, the maximum length of the root system occurred by treating their seeds with Fe NP at the concentration of 10^{-7}%, significantly ($P \leq 0.05$) exceeding the control by 9.2% and 14.5%, respectively. However, a further increase in the content of Fe NP led to inhibiting growth processes. By nano-based seed treatment, the improvement in growth has been evident in other plant species, like rice (Prerna *et al*., 2021), *Phaseolus vulgaris* (Savassa *et al.,* 2018), *Brassica napus* (El-Badri *et al.,* 2021), *Citrullus lanatus* (Kasote *et al.,* 2019), and *Triticum aestivum* L. (Joshi *et al*., 2018).

Iron nanoparticles had a particularly strong effect on the accumulation of dry biomass in seedlings per plant. On average, across the spring durum wheat cultivars, with Fe NP treatment, the seedlings' dry weight increased by 19.2%, and the dry weight of the root system enhanced by 18.4%. At the same time, the formation of the aerial part occurred most actively by treating the cultivars Orenburgskaya-21, Milyana, Bourbon, and Tselinnitsa with Fe NPs (10^{-4}%) and the cultivars Bezenchukskaya Zolotistaya and Luch-25 at the 10^{-7}% concentration. On average, the significant ($P \leq 0.05$) excess over the control variant was 10.7% to 25.5%. However, the cultivar Orenburgskaya-21 resulted as the most responsive as compared with the other durum wheat genotypes.

By treating seeds with Fe NPs, the development of the underground part of durum wheat was identical. The maximum significant ($P \leq 0.05$) enhancement relative to control samples was 25.0%, 15.8%, 9.4%, and 12.0% in the cultivars Tselinnitsa, Orenburgskaya-21, Milyana, and Bourbon, respectively, with the NP concentration at 10^{-4}%. In this group of cultivars, the sprout and root system weight declined with a decrease in the iron concentration during pre-sowing seed treatment and the concentration ranged from 10^{-6}% and lower. Meanwhile, no significant increase in the indicator emerged. Pre-sowing treatment at the NP concentration (10^{-7}%) of the durum wheat cultivars Bezenchukskaya Zolotistaya and Luch-25 notably ($P \leq 0.05$) raised the root mass by 24.4% and 6.0%, respectively, compared with the control.

The two-factor analysis of variance established a meaningful ($P \leq 0.05$) influence of the durum wheat genotypes on the variability of studied characters, such as, the length of the sprouts and roots, the total length of the root system, and the dry weight of the sprouts and root system, with the highest shares of 82.3%, 64.4%, 73.9%, 75.9%, and 21.4%, respectively (Table 4). The metal concentration in the polymer composition considerably influenced the length of the embryonic root, the total length, and the dry weight of the root system. Based on the traits under study, the share of influence was 20.2% to 70.7%. The combination of factors affected the length of the sprout, with an influence share of 12.3%.

For normal metabolism, the plants need trace elements, which participated in catalytic redox reactions. Nutrient deficiency can lead to growth retardation and leaf necrosis due to a disruption of various plant processes, and then, death (Rabinovich and Lyubimova, 2021). The plant cell walls act as a barrier, preventing any external agent from entering. Consequently, only nanoparticles with a diameter smaller than the diameter of the cell wall pores can easily penetrate such wall and reach the plasma membrane (Moore, 2006; Navarro *et al.*, 2008).

Currently, numerous studies have progressed on the effects of metal NPs on seed germination (Ahmad *et al.*, 2022). It was also noteworthy the NPs help effectively use the nutrients of the seed, enhance water absorption and the activity of enzymes, including catalase, peroxidases, amylases, and accumulate reactive oxygen species, characterizing the end of the dormant period (Rastogi *et al.*, 2017). The NPs have a greater potential for supplying plant nutrients (Liu and Lal, 2015). Pre-sowing treatment of seeds with

Table 4. Two-factor analysis of variance of variability of morphological parameters in durum wheat seedlings.

Source of variance	d.f.	Sprout length		Average length of the spine		Total length of root system		Dry weight of sprout		Dry weight of root system	
		SS	Sf (%)	SS	Sf (%)	SS	Sf (%)	SS	Sf (%)	SS	Sf (%)
General	89	87.475	-	16.512	-	248.698	-	10.852	-	5.055	-
Factor A	5	136.662*	82.277	20.274*	64.445	2220.043*	73.912	12.162*	75.957	2.130*	21.368
Factor B	4	4.165	3.515	1.104*	20.283	530.089*	22.060	1.648*	12.865	5.639*	70.698
AB Interaction	20	14.062*	12.373	4.062	11.191	462.187	3.846	3.345	5.222	1.360	3.412
Repetition	2	1.821	0.085	0.011	1.068	4.278	0.123	0.102	1.419	0.027	0.098
Random deviations	58	32.584	1.833	5.1338	4.079	2.535	0.007	4.125	2.146	2.001	1.672

Note: d.f. = degrees of freedom, SS = mean square, Sf = share of factor influence. Factor A = durum spring wheat cultivars (Tselinnitsa, Orenburgskaya-21, Milyana, Bourbon Bezenchukskaya golden, Luch-25); Factor B = options for pre-sowing treatment of seeds with low concentrations of Fe 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}% and without treatment. * Differences between variants were considered statistically significant at $p \leq 0.05$

NPs positively stimulate the viability of seedlings, activating the metabolic system of plants, which has a beneficial effect on the growth of crops (Paparella *et al.*, 2015).

The latest work investigated the effects of iron nanoparticles on the development of seedlings during the juvenile period. Nano-sized iron is a common component of fertilizers, considered as dual-action element in crop plants. As an essential micronutrient controlling numerous physiological processes (Feng *et al.*, 2022), Fe in its ionic form can be toxic and harmful to plants. The study of the biological activity of iron nanoparticles used the *Escherichia coli K12 TG1* bioluminescence test system to reduce potential toxicity (Deryabin *et al.,* 2016) and determine the non-toxic concentrations. The results revealed the concentration range of 1.5×10^{-3} mg/ml and higher have a pronounced bactericidal effect, and upon contact for more than 30 minutes, caused the death of 20% to 100% of bacteria. However, a safe concentration of Fe NPs was 8×10^{-4} mg/ml and lower, causing no inhibitory effect on the luminescence parameters.

By studying the effect of pre-sowing treatment of durum wheat seeds, the seed germination energy reached enhancement by 34%–63%, which in field conditions, can reduce the time for the emergence of vigorous shoots. However, the germination rate itself was high in all variants of the experiment, and treatment with NPs caused its increase by 2%–9%. After treatment with nanoparticles, the study of the morphometric parameters of seedlings showed iron raising the plant growth; however, the intensity depends on the cultivar and the concentration of the metal in the polymer film.

Using Fe NP at the concentration of 10^{-4}%, the best morphometric indicators resulted in the cultivars Tselinnitsa, Orenburgskaya-21, Bourbon, and Milyana, giving a significant increase in sprout length (16.2%–20.6%), root length (8.3%–13.5%, the total length of the root system (6.9%–19.4%), and the accumulation of plant dry mass (9.4%–25%) compared with the control treatment. Pre-sowing treatment of the durum wheat cultivars Bezenchukskaya Zolotistaya and Luch-25 with NPs (10^{-7}%) also showed significant ($P \leq 0.05$) increase in shoot length (15.3%–20%), the length of the root system (9.2%–14.5%), and the root weight (6.0%–24.0%) compared with the control treatments. The rise in growth performance under the influence of nanoparticles can be because nutrients, such as Fe, stimulate the biosynthesis of chlorophyll and redox processes in plants, which has a positive effect on plant growth (Briat *et al.,* 2015; Tamrazov, 2022; Alhabbar *et al*., 2023; Khanishova and Azizov, 2023).

However, in the presented studies, it was evident that one group of cultivars responds to higher metal concentrations, and the other to lower ones. Studying the influence of Fe NPs in the context of durum wheat cultivars demonstrates the maximum influence of the genotype on morphometric indicators, such as, above-ground weight of the shoots (64.4%–82.3%). The development of the root system largely acquired influences from the metal concentration in the polymer composition (20.2%–70.7%). It can be due to several possible reasons; firstly, the different cultivars were able to absorb and use nutrients from fertilizers and soil at different degrees, which also reflected in the size and chemical composition of the grain formed (Bobrenko *et al.,* 2004; Bobrenko, 2017). Secondly, some crop cultivars adapt better to environmental conditions and may be more responsive to the addition of mineral elements (Ermokhin *et al.,* 2003; Ermokhin and Bobrenko, 2004).

CONCLUSIONS

Iron NPs have the highest biological activity, with an expressed bactericidal effect. The toxic effect of iron nanoparticles on the bioluminescence of the *Escherichia coli K12 TG1* emerged at the concentration of 1.5×10^{-3} mg/ml and higher, thus, the recommendation to use the concentration range of 8×10^{-4} mg/ml and lower. By treating with NP concentration (10^{-4}%), the durum wheat cultivars Tselinnitsa, Orenburgskaya-21, Milyana, and Bezenchukskaya Zolotistaya occurred with the maximum increase in morphological parameters, while in cultivars Bourbon and Luch-25, the effective concentration of Fe NP was 10^{-7}%. The study proposes the established optimal concentrations of NPs for further production tests in the field.

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