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WHEAT (*TRITICUM AESTIVUM* L.) RESPONSE TO SILVER NANOPARTICLES THROUGH MORPHOPHYSIOLOGICAL VARIATIONS

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SUMMARY

Intensive development of nanotechnologies makes it viable to determine the influence of nano-compounds on the productive properties of crop plants, considering the environmental factors due to current climate change. The presented study aimed to investigate the effects of silver nanoparticles on the seeds' ability to germinate, variability of morphophysiological traits during the vegetation period, and grain yield of spring soft wheat (*Triticum aestivum* L.). The wheat's pre-sowing seed treatment with silver nanoparticles (silver nanoparticles in aqueous solution of 0.5%, 1.0%, and 1.5%) reached evaluation for variations in morphophysiological traits in three cultivars, viz., Omskaya-36, Tyumenskaya-29, and Novosibirskaya-31. All the seed treatments, carried out once, had the seeds kept in prepared solutions for three hours, as well as, the control (in distilled water only). Field experiments took place in 2018–2020 at the biostation 'Lake Kuchak' of Tyumen State University, Tyumen, Russia. Seed treatment (Ag 1.0%) contributed to an increase in field seed germination in the cultivar Omskaya-36 (by 23.8%) during 2019. For grain yield, positive results occurred in the cultivar Omskaya-36 (by 23.8% compared with the control) in 2019–2020, while in Tyumenskaya-29 (by 25.9%) in all years of the study, and cultivar Novosibirskaya-31 (by 12.8%) in 2019–2020.

Keywords: Spring soft wheat (*T. aestivum* L.), cultivars, germination rate, flag leaf, chlorophyll content, grain yield

Key findings: The article discusses the results of studying the response of spring soft wheat (*T. aestivum* L.) cultivars to the use of silver nanoparticles, depending on the genotype, concentration of the material solution, and weather characteristics of the growing season.

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INTRODUCTION

In world agriculture, the wheat (*Triticum aestivum* L.) leads as the main food crop, taking first position for sown area (221.96 million hectares), grain yield (776.5 million tons year^{-1}), and trade. Over the past five years, a dynamic increase has materialized in the sown area of spring wheat cultivars in the Tyumen Region, from 384,800 (2018) to 416,700 hectares (2022) (ROSSTAT, 2022). The spring wheat grain yield has averaged around 2.08 t/ha over the past five years. The variations in the grain yield through the years ranged from 1.60 to 2.66 t/ha, with a significant decrease in the arid year of 2021, which indicates the dependence of productivity on abiotic and biotic environmental factors.

Lack of precipitation with increased average daily air temperature led to inhibit growth processes, which results in a decreased grain yield. Therefore, one of the most important tasks is the search for techniques that enhance the adaptive and productive properties of wheat. Promising areas include the introduction of new technologies into agriculture, including the use of nanoparticles of various metals (Korotkova, 2017; Mittal *et al.*, 2020; Singh *et al.*, 2021).

Nanoparticles are becoming the main component of phytonanotechnology due to their antimicrobial properties and ability to control phytopathogens (Jiang *et al*., 2021; Hoang *et al*., 2022). The electrical neutrality property of nanoparticles contributes to their uniform distribution around the seeds, which provides reliable protection against phytopathogenic microorganisms. The gradual oxidation of nanoparticles in the soil has an inhibitory effect on vital activities of the pathogens, thereby improving the conditions for plant growth and development (Korotkova, 2017). Therefore, in crop production, nanotechnology is primarily applicable as nanofertilizers and nanopesticides to improve growth, increase plant resistance to insect pests and diseases, and boost yield (Shang *et al*., 2019; Bhatt *et al.*, 2020). In the studies of Asanova *et al*. (2018), high concentrations of silver nanoparticles reduced the proportion of germinated conidia of the phytopathogenic fungus *Bipolaris sorokiniana* (Sacc.) Shoemaker and lessened the growth rate of mycelium of the xylotrophic fungi *Pleurotus ostreatus* (Fr.) Kumm.and *Neonothopanus nambi* (Speg.) R.H.Petersen & Krisai.

Nanotechnology can ensure food security by improving crop production. Nanoparticles can enhance the growth and yield of various crop plants (Zea and Salama, 2012; Yang *et al*., 2018; Khan *et al*., 2021). Many assumed silver nanoparticles increase the efficiency of plants by using nutrients (Hafiz *et al*., 2015). Past studies also revealed the use of silver nanoparticles protects wheat plants from heat stress by improving the morphological parameters, i.e., roots, sprouts, and leaf surface area. They accelerate the mobilization of spare organic matter in cells, with silver nanoparticles increasing the production of reactive oxygen species, suppressing pathogen development, and enhancing plant immunity (Iqbal *et al*., 2019).

However, the technologies using nanoparticles have not yet reached full development. Silver nanoparticles enhanced the seed germination, optimized plant growth and development, and increased yields, by using the prepared solutions with recommended concentrations (Maslobrod *et al*., 2014; Matras *et al*., 2022). A study found silver nanoparticles synthesized using aqueous extracts of *Nigella sativa* seeds had no significant effect on seed germination. Meanwhile, the roots and coleoptiles’ length decreased, the biomass of seedlings increased, and genotoxicity detection was apparent with high concentrations (Ezzat *et al*., 2022). In light of above discussion, the presented study sought to investigate the effect of silver nanoparticles on seed germination ability, variability of morphophysiological traits, and grain yield of spring soft wheat (*T. aestivum* L.) in the Northern Trans-Urals, Russia.

MATERIALS AND METHODS

Study location

The study on spring soft wheat (*T. aestivum* L.) began in 2018 up to 2020 at the University of Tyumen (UTMN), Tyumen, Russia. The field research progressed at the experimental site of the UTMN Biological Research Station, Lake Kuchak, District Nizhnetavdinsky, Tyumen Region, Russia (57°20′57.3″ N 66°03′21.8′E).

Weather conditions

In 2018, the growing season's general characteristic was slightly arid, according to the hydrothermal coefficient (HTC = 1.3). Seed germination and seedlings' emergence in May took place with excess moisture (82 mm or 182% of the norm) against the background of low average daily air temperatures (-3.1 °C at the long-term average). In June, the air temperature was below the long-term average by 2.1 °C and amounted to 15.0 °C, and the total precipitation was 58.3 mm (112% of the norm). However, at the heading stage in July, wheat plants experienced less moisture (50.5 mm or 57.1% vs. the norm), with the highest average daily air temperature (1.8 °C above normal). In August, the total precipitation was 117.7 mm (187% of the norm), and the average daily air temperature exceeded the long-term average by 0.3 °C. These weather conditions are considerably favorable for the development of phytopathogenic fungi – causative agents of leaf diseases of wheat (Figure 1).

The crop season in 2019 had a wet classification, according to the hydrothermal coefficient (HTC = 1.5). The sowing commenced by the 20th of May, and the moisture and heat supply conditions were relatively optimal for seed germination. Compared with the average long-term values, the average daily air temperature for May was 1.6 °C higher; the total precipitation was 90.0% of the norm. In June, low air temperatures (2.0 °C below normal) coincided with the phenological boot stage against the background of excess moisture (142% of the normal). During the heading, flowering, and fertilization of spring wheat, the air temperature was 19.7 °C vs. the norm (18.8 °C), and in July, precipitation exceeded the long-term average by 21.0%. The extremely uneven distribution of precipitation was also evident throughout the month. In August, the grain ripening materialized under the prevailing conditions of heat supply close to the long-term values, and the excess in precipitation amounted to 19% (Figure 1).

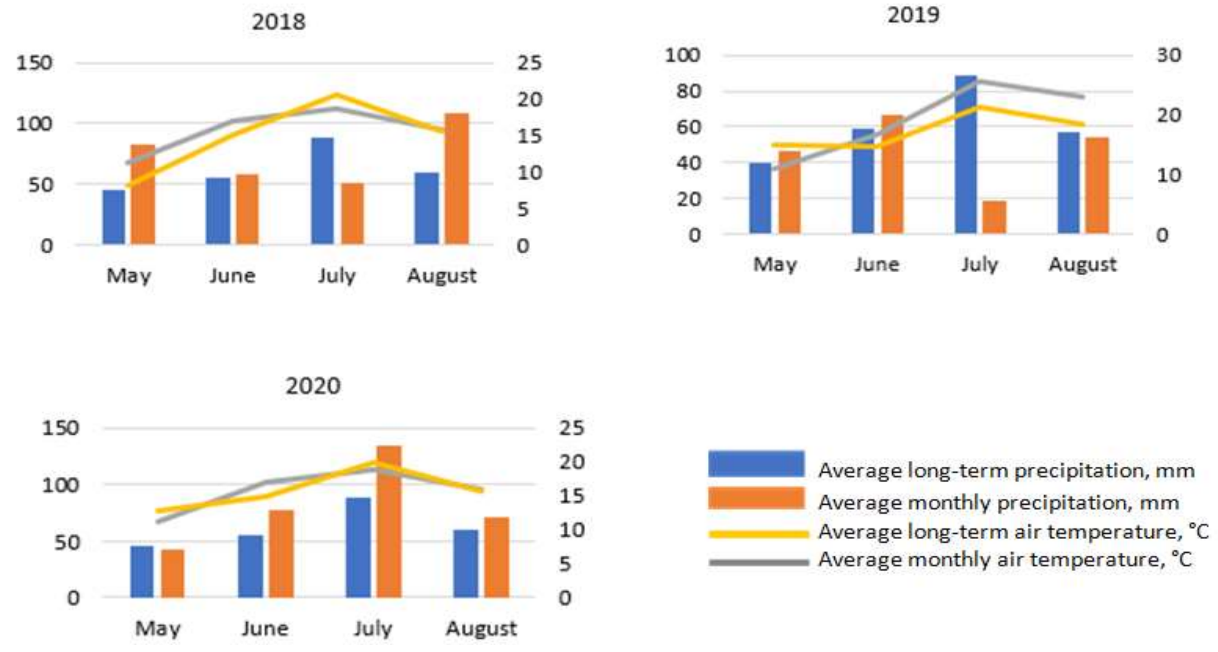


Figure 1. Hydrothermal conditions of growing seasons, 2018–2020.

The growing season in 2020 was quite arid (HTC = 0.89). The conditions for seed germination and seedling formation were favorable with heat supply, since in May, the average daily air temperature exceeded the norm (11.3 °C) by 3.6 °C. The total precipitation was 50 mm (112% of the norm). However, an uneven distribution mostly appeared throughout the month. In June, a cold snap manifested – at the normal monthly average temperature of 17.1 °C, the variation reached -2.5 °C, and the total precipitation was 23.0% above the norm. Heat and water stress affected the spring wheat plants in July. At a mean rainfall of 89 mm, only 19 mm (21%) fell. According to meteorological observations, the average monthly air temperature was 21.5 °C, with the variation of +2.7 °C vs. the norm. In August, the hot weather continued, with the air temperature of 18.3 °C (2.5 °C above normal). More precipitation occurred compared to the previous month (54 mm); however, it was less than the norm (60 mm) (Figure 1).

Thus, the processes of fertilization, formation, filling, and ripening of the soft spring wheat grain incurred influences from the varying weather conditions of the growing seasons of 2018–2020. These weather conditions were significantly different from the long-term average values of the South of the Tyumen Region, Russia. During the study, it was also critical to understand the response of the soft spring wheat cultivars to environmental factors with pre-sowing seed treatment by silver nanoparticle solutions, as well as, the control.

Breeding material

Three spring soft wheat cultivars (Omskaya-36, Tyumenskaya-29, and Novosibirskaya-31) were the used samples in the study. The cultivar Omskaya-36 (var. *lutestens*) is a variety bred at the Omsk Agricultural Scientific Center and Agricultural Complex Kurgansemena, with the LLC included in the State Register for the Ural (9) and West Siberian (10) regions. The said genotype became recommended for cultivation in the Altai Territory, Republic of Bashkortostan, Kurgan and Omsk regions, Russia.

The cultivar Tyumenskaya-29 (var. *lutestens*), bred by the Tyumen Scientific Center SB RAS, gained inclusion in the State Register for the West Siberian (10) region, recommended for cultivation in the Tyumen Region, Russia. The cultivar Novosibirskaya-31 (var. *lutestens*), bred by the Federal Research Center Institute of Cytology and Genetics, Siberian Branch of Russian Academy of Sciences, reached the list of the State Register for the West Siberian (10) and East Siberian (11) regions. The said genotype was a chief recommendation for cultivation in the Novosibirsk Region, zones of the sub-boreal forest of the lowland, the sub-boreal forest of the foothills, the northern forest-steppe of the lowland, and the northern forest-steppe of the foothills.

For pre-sowing seed treatment of spring soft wheat cultivars, the study used a prepared solution of ‘ARGITOS AGRO,’ provided by the Research and Production Enterprise ‘Nanosphere,’ Moscow, Russia. The biopreparation is the particles of metallic silver dispersed in a liquid medium to form a colloidal solution with an average size of nanoparticles 1–2 nm (nanometers) (Argitos.com, 2022).

Research methodology

In the solution, the initial concentration of silver nanoparticles used was 1000 ppm. The prepared solutions comprised three different concentrations (drug + distilled water), i.e., 0.5% = 0.2 + 99.8 ml, 1.0% = 0.4 + 99.6 ml, and 1.5% = 0.6 + 99.4 ml. Wheat seeds’ treatment happened once, according to the following scheme: a) Control – distilled water, b) Ag 0.5%, c) Ag 1.0%, and d) Ag 1.5%. The experimental wheat seeds bore soaking in the different nanoparticle solutions and control (in distilled water) for three hours. The technology for pre-sowing seed treatment was environmentally friendly, requiring minimal financial costs.

Sowing of seeds transpired by the 20 and 30 days of May, on plots with an accounting area of 1 m^2, manually using a planting marker, at the rate of 600 viable seeds per 1 m^2, with a row spacing of 20 cm, in three replications. The soil was soddy-podzolic, sandy loam in granulometric composition, humus content (3.67%), acidity in the salt extract (close to neutral = pH 6.6), mobile forms of phosphorus (433.3 mg/kg of soil), and exchangeable potassium (234.0 mg/kg). The experiment also proceeded without applying mineral fertilizers to the soil and chemical plant protection measures.

Field germination is equivalent to the ratio of the number of seedlings to the number of seeds sown and expressed in percentage. At the heading stage, the plant height measurement progressed at different points of the plot (n=10 plants per plot), also determining the linear dimensions of the flag leaf (length and width). The assessment of functional state of wheat plants considered the variations in the chlorophyll content in the flag leaf using a portable SPAD-502 meter (Minolta, Tokyo, Japan). It measured the transmission coefficient of leaves in red (650 nm) and near infrared (940 nm) wavelengths at the different phenological stages (boot, heading, flowering, milky, and dough stage of the grain (Hafsi *et al*., 2013).

Harvesting the plants ensued manually, detecting the various morphological traits, grain yield, and 1000-seed weight (GOST-12042-80). Data on average daily air temperature and precipitation came from the reference and information portal of the Weather and Climate (2022). The actual indicators bore comparison with the average long-term values (conditional norm) of the average daily air temperature and precipitation for the period of 1936–2020. The calculations of hydrothermal coefficient (HTC) values according to the following formula (Selyaninov, 1930):

$$HTC = \frac{R}{0.1} * \sum t,$$

Where, R is the total precipitation per month in mm, $\sum t$ = the total average daily air temperature values above 10 °C.

Statistical analysis

Statistical compilation of the recorded data continued according to proven methods (Lakin, 1980; Dospekhov, 1985), using the Microsoft Excel spreadsheet processor and STATISTICA 6.0 software (StatSoft, Inc., USA). The determination of average values (Xav.), errors of means (Sx), and statistical significance of the differences between the average values of variations employed the Student's t-test. The correlation analysis also ensued.

RESULTS AND DISCUSSION

Seed germination

Seed germination is one of the crucial indicators characterizing the adaptive properties of a crop plant from the beginning of ontogenesis, which depends upon the seed quality, as well as, environmental and agrotechnical factors (Vasko, 2012). The spring soft wheat (*T. aestivum* L.) growth and development, reliant on the number of shoots with productive ears at the ripening stage, depends on the number of seedlings, their vigor, and environmental conditions (Zakharova, 2016). Testing of silver nanoparticles on wheat plants allowed us to identify the optimal concentrations for improving the seed germination and increasing the morphological parameters of seminal roots (length, wet, and dry weight) (Sabir *et al.*, 2018).

According to the presented results, the highest positive effect of the seed treatment with silver nanoparticles was evident in the crop season 2019 (Table 1). Field germination of seeds in the experimental variants was significantly higher than the control by 15.2%–23.8%. In cultivars Omskaya-36 and Novosibirskaya-31, an increase in the field germination index was notable with all the concentrations of silver nanoparticle solution, except in cultivar Tyumenskaya-29 at the weak concentration (0.5%). In crop season 2018,

Table 1. Effect of silver nanoparticles on the variability of field germination of seeds.

Experiment option	2018	2019	2020
		Xav. ± Sx (%)	
Omskaya-36			
Control	80.5 ± 0.5	61.8 ± 5.1	65.4 ± 4.0
Experiment 0.5% Ag	77.5 ± 7.5	85.6 ± 2.5*	69.9 ± 3.9
Experiment 1.0% Ag	79.7 ± 1.0	79.9 ± 0.7**	61.4 ± 4.5
Experiment 1.5% Ag•	-	-	57.1 ± 4.1
Tyumenskaya-29			
Control	62.5 ± 5.5	65.8 ± 4.0	60.1 ± 4.4
Experiment 0.5% Ag	64.3 ± 6.0	80.9 ± 1.6**	67.8 ± 3.6
Experiment 1.0% Ag	74.7 ± 3.0*	78.3 ± 5.4	70.9 ± 4.9
Experiment 1.5% Ag	-	-	64.5 ± 4.8
Novosibirskaya-31			
Control	65.5 ± 1.5	62.4 ± 1.2	57.5 ± 4.9
Experiment 0.5% Ag	74.2 ± 2.5***	79.8 ± 1.2 **	57.2 ± 4.9
Experiment 1.0% Ag	83.5 ± 3.5***	77.6 ± 2.3**	65.8 ± 8.0
Experiment 1.5% Ag	-	-	48.0 ± 4.4

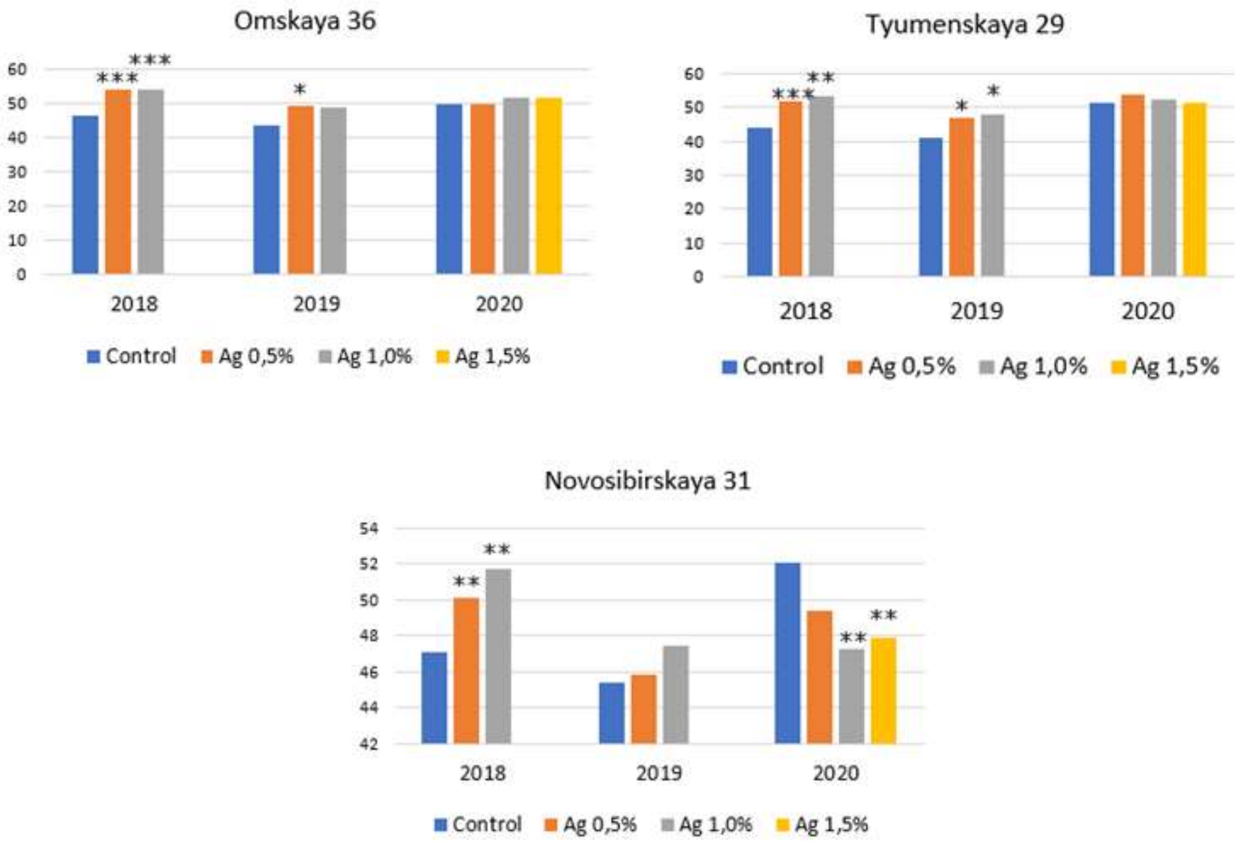
Note: Significant differences at control: * – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$
•The 1.5% Ag option was included in the experimental design in 2020.

significant differences between the various seed treatments and the control treatment appeared in the wheat cultivars Novosibirskaya-31 (0.5% and 1.0% Ag) and Tyumenskaya-29 (1.0% Ag) (8.7% and 18.0%, respectively, above the control). Experimental variants with a high concentration (1.5%) remained at the control level. In crop season 2020, nonsignificant differences existed between the experimental and control versions, which may be due to lack of precipitation during the sowing and germination stages. Rajeew *et al*. (2018) reported seed soaking with metal nanoparticles also showed improved germination and growth traits in wheat seedlings.

The mechanisms explaining the effects of nanoparticles on seed germination have not reached full clarification. However, past studies explained the positive effects of silver nanoparticles to form new pores in the seed coat during penetration, which can increase the influx of nutrients into the seed and improve seed germination and seedling growth (Tkalec *et al*., 2019). According to Qian *et al.* (2013), nanoparticles lead to a decrease in water absorption, causing variations in the transcription of aquaporin genes and negatively affecting plant growth.

Plant height, flag leaf area, and chlorophyll content

Silver nanoparticles are vital in improving the wheat plants' growth processes during the cultivating season. The results showed in cultivar Omskaya-36, the plant height at the beginning of heading incurred substantial influence from the seed treatment with silver nanoparticles in 2018 (0.5% and 1.0% concentrations) and 2019 (0.5% concentration). With such concentrations of silver nanoparticle solution, the plant height enhanced by 7.6–7.8 cm and 5.5 cm, respectively, in comparison with the control treatment during the three years of study. In the cultivar Tyumenskaya-29, the plant height under the influence of both concentrations increased by 7.8–9.2 cm in 2018 and 5.8–6.8 cm in 2019. However, in 2020, the seed treatment variants were at par with the control treatment for the plant height. In the cultivar Novosibirskaya-31, seed treatment stimulated the plant growth and plant height (by 3.0–4.6 cm at the control) in 2018. In 2020, the inhibitory effect of silver nanoparticles' high concentrations (1.0% and 1.5%) on the plant growth manifested, which may correlate with stress load from weather conditions (Figure 2).



Note: Significant differences vs control: * – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$

Figure 2. Effect of silver nanoparticles on the height of plants at the heading stage

Yang *et al*. (2018) studied the high concentrations of silver nanoparticles, which also led to a decrease in plant height and biomass in the wheat crop.

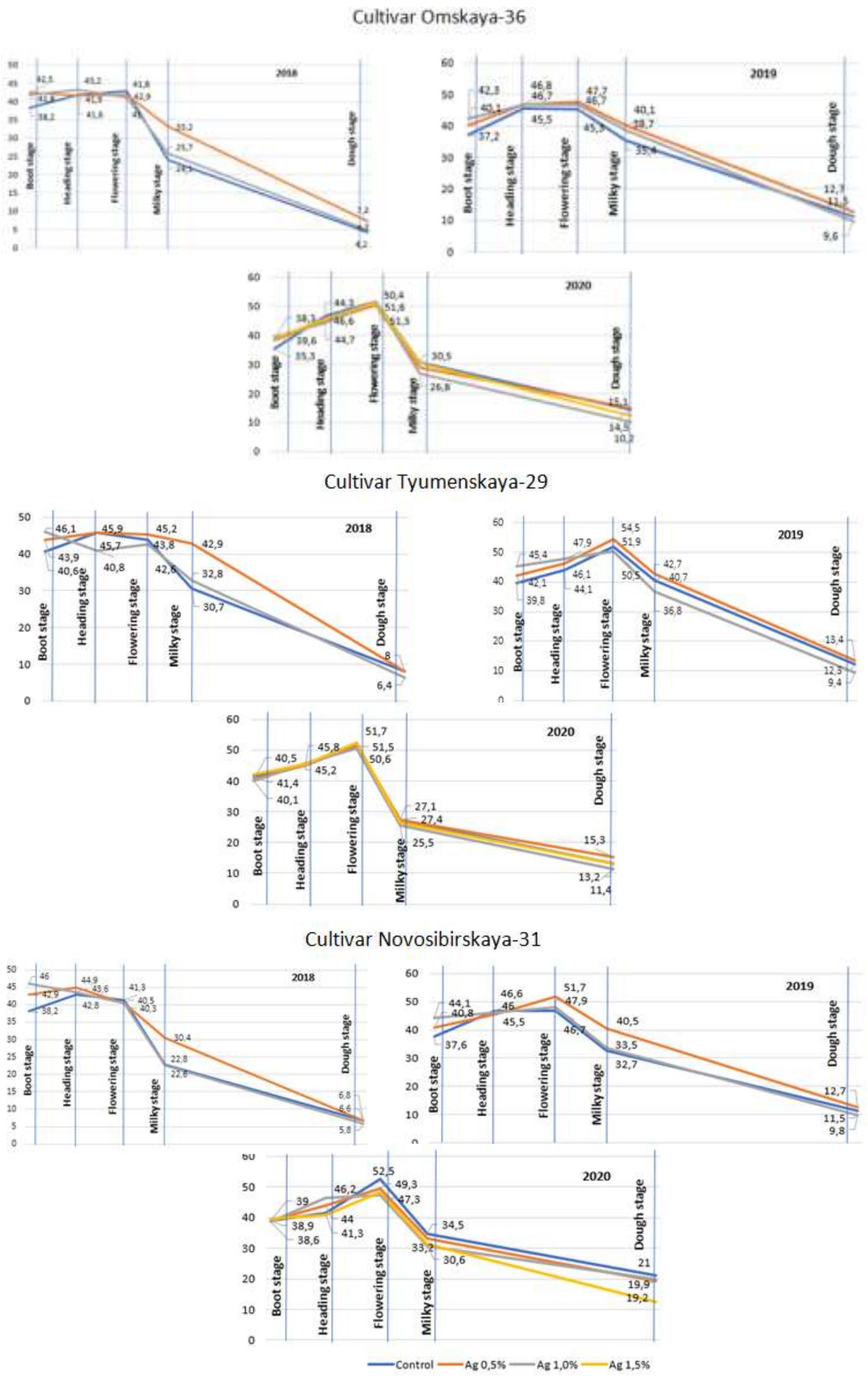
Flag leaf is one of the most influential elements of grain crops, ultimately determining the yield potential, and the contribution of the flag leaf to the harvest reaches 50% in wheat (Gudkova, 2008; Liu, 2018) and barley (Schennikova *et al*., 2010). One of the sources of wheat grain assimilates is leaf photosynthesis, especially in the flag leaves in wheat (Ba *et al*., 2020). In the cultivar Omskaya-36, the stimulating effect of silver nanoparticles on the flag leaf length was evident in 2018 (0.5% Ag) and 2019 (0.5% and 1.0% Ag). The concentration of 1.0% contributed to an increase in the width of the leaf blade in 2018 (Table 2). However, the leaf length of the cultivar Tyumenskaya-29 with seed treatments did not differ from the control treatment for the entire study period. One should also note the said wheat cultivar plants formed wider leaves after the seed treatment in 2018. The cultivar Novosibirskaya-31's response to nanomaterial appeared with an increase in the leaf blade length in the first two years of the study, while an enhancement in the leaf blade width during 2019 and 2020. Inclusion of the high concentration of the nanomaterial solution in the experimental design during 2020 proved to be effective for developing the flag leaf in the cultivar Novosibirskaya-31. The findings of Sarwar *et al.* (2023) revealed silver nanoparticles significantly restored physiological functioning of the leaves and grain yield formation at maturity in wheat.

Photosynthesis is a considered main source of wheat grain yield formation under stressful conditions, and by loss of chlorophyll, the leaf area assimilation decreases, as well as, their functioning duration (Yang *et al*., 2022). The cultivar Omskaya-36 emerged with the highest chlorophyll content in the flag leaf cells during the heading and flowering period by comparing the years and variants of the experiment (Figure 3). During arid season in 2020, the chlorophyll pigment increased in the leaves compared with the previous two years (2018 and 2019), which might be due to wheat plants' response to the stress factors. Seed treatment with the nanomaterial slowed down the chlorophyll degradation and leaf aging at the milky to dough stages compared with the control in 2018, 2019, and 2020, by 4.6%, 6.9%, and 11.2%, respectively. However, at the last measurement at the dough stage, the chlorophyll content exceeded the control in the variant of seed treatment with nanosolution at 0.5% concentration. In the cultivar Tyumenskaya-29 leaves, after seed treatment (Ag 0.5%), a significant slowing down occurred with a chlorophyll content decrease compared with the control treatment in 2019 (by 25.7%).

With insufficient moisture and against the background of increased average daily air temperature during the crop season of 2020, the duration of photosynthetic processes in the flag leaves of the experimental versions increased by 4.9% (Figure 3). In the cultivar Novosibirskaya-31, the seed treatment with the nanomaterial accelerated the process of chlorophyll destruction during the milky to dough stage by 3.6%–8.1% in the crop seasons of 2018 and 2019. Under stressful conditions in 2020, a positive effect resulted after treating the wheat seeds with the nanomaterial (1.0%), and the chlorophyll content in the flag leaves decreased by 10.7 SPAD units (by 13.5 SPAD units in the control) (Figure 3). Applying nanoparticles increases the functionality of photosynthesis and also promotes plant growth and productivity (Vatankhah *et al.,* 2023). In wheat genotypes, the yield stability had linkages with the physiological functioning of leaves and maintaining the integrity of cell membranes (Ullah *et al.*, 2022). Silver nanoparticles can contribute to improving the efficiency of photosynthesis in wheat crops (Kannaujia *et al*., 2022) and increasing the mobility and absorption of nutrients by wheat plants under drought conditions (Ahmed *et al*., 2021; Bakry *et al*., 2024).

The spring wheat cultivar Omskaya-36 stood out for grain yield without using the silver nanoparticles during the three years of study (Table 3). The positive effect of the seed treatment was apparent in the crop season 2019 in the variant with a weak concentration (the yield was 9.7% higher than the control). In 2020, a positive response of the cultivar to all concentrations of the nanomaterial was prominent, including the highest dose (1.5%), which provided the maximum increase of 14.3% in grain yield compared with the control. Correlation analysis revealed a direct relationship of grain yield with plant height (r = 0.51), flag leaf length (r = 0.41) and width (r = 0.24), the significant relationship with the chlorophyll content of the flag leaf at the milky stage (r = 0.86), and mass of 1000 grains (r = 0.77). Pre-sowing preparation of the Tyumenskaya-29 seeds contributed an elevation in yield during the three study years. The largest excess of grain productivity over the control appeared in 2018 in variants with nanomaterial concentrations of 0.5% and 1.0% (24.3% and 25.9%, respectively).

Positive results resulted with the use of silver nanoparticles in arid conditions in 2020, and with concentrations of 0.5% and 1.0%, the yields were 11.9%–16.6% higher than the control. The effect of the nanomaterial on the grain yield was less pronounced during the crop season of 2019. The formation of grain yield of Tyumenskaya-29 seeds depended on the described characteristics; however, the strength of relationship with each of them was weak. The positive responsiveness of the cultivar Novosibirskaya-31 to the effect of silver nanoparticles (1.0% and 0.5%) was noteworthy in 2019 and manifested with an increased yield of 9.8%–12.8%. In 2020, the grain productivity was significantly higher with the topmost nanomaterial concentration (1.5%) versus the control. The grain yield revealed a positive correlation with the plant height (r = 0.57) and flag leaf length and width



Cultivar Omskaya-36

Cultivar Tyumenskaya-29

Cultivar Novosibirskaya-31

Figure 3. Dynamics of chlorophyll accumulation and degradation in the leaves of soft spring wheat during growing seasons, 2018–2020, SPAD units.

Table 3. Effect of silver nanoparticles on the yield and weight of 1000 spring wheat seeds, 2018–2020.

Experimental options	Yield, g/m^2			Weight of 1000 seeds, g		
	Xav. ± Sx			Xav. ± Sx		
	2018	2019	2020	2018	2019	2020
Omskaya-36						
Control	356.4 ± 32.0	239.1 ± 12.3	299.1 ± 3.2	39.0 ± 1.89	37.9 ± 1.8	38.5 ± 1.9
Experiment 0.5% Ag	334.2 ± 37.9	262.4 ± 10.5**	329.8 ± 3.4***	35.3 ± 2.89	38.4 ± 1.4	36.9 ± 2.8
Experiment 1.0% Ag	338.8 ± 28.6	247.6 ± 4.7	319.7 ± 3.0**	37.2 ± 1.48	35.8 ± 1.6	36.5 ± 1.4
Experiment 1.5% Ag	-	-	341.9 ± 3.2***	-	-	37.8 ± 1.5
Tyumenskaya-29						
Control	239.8 ± 7.4	193.2 ± 31.7	287.2 ± 5.1	30.2 ± 1.17	30.4 ± 1.2	30.3 ± 1.1
Experiment 0.5% Ag	298.0 ± 2.8***	202.8 ± 2.1**	321.4 ± 2.6**	30.8 ± 1.59	29.0 ± 1.5	29.9 ± 1.6
Experiment 1.0% Ag	302.0 ± 10.5**	213.4 ± 9.0**	334.8 ± 2.4***	30.8 ± 1.09	30.4 ± 1.3	30.6 ± 1.0
Experiment 1.5% Ag	-	-	291.8 ± 3.1*	-	-	28.7 ± 1.3
Novosibirskaya-31						
Control	314.6 ± 25.3	156.6 ± 23.8	261.7 ± 2.8	29.2 ± 1.48	24.8 ± 0.7	27.0 ± 1.4
Experiment 0.5% Ag	296.4 ± 20.4	176.6 ± 20.4**	230.4 ± 4.6**	28.5 ± 2.57	25.4 ± 1.4	24.4 ± 2.5
Experiment 1.0% Ag	252.4 ± 18.4	172.0 ± 10.7**	203.4 ± 3.1***	28.0 ± 0.5	26.1 ± 2.1	27.0 ± 0.5
Experiment 1.5% Ag	-	-	267.2 ± 2.5*	-	-	25.9 ± 1.2

Note: Significant differences vs control: * – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$.

($r = 0.48$ and $r = 0.51$, respectively). With the chlorophyll content, the considerable correlation coefficient was prevalent at the heading stage of wheat plants ($r = 0.73$). The cultivar Omskaya-36 seeds were larger than the two other cultivars Tyumenskaya-29 and Novosibirskaya-31 in both control and experimental variants, and the same was also valid with the 1000-seed weight. Although, nonsignificant differences emerged between the control and seed treatment variants with silver nanoparticles for the 1000-seed weight. Silver nanoparticles can contribute in improving the physiological and yield related traits in wheat crop (Ismailova and Azizov, 2022; Atia and Oraibi, 2024).

CONCLUSIONS

The positive effect of silver nanoparticles on the field seed germination of spring soft wheat (*T. aestivum* L.) resulted in relatively favorable hydrothermal conditions (2018–2019) and decreased with insufficient moisture in the soil during 2020. Under moisture deficiency and increased air temperature, the cultivar Novosibirskaya-31 responded more to the silver nanoparticles with higher concentration (1.5%) by reducing the plant height in the earing phase; however, it formed larger flag leaves with delayed degradation of chlorophyll during the flowering to ripening stage. Pre-sowing treatment of wheat seeds with nanomaterial concentration (0.5%) contributed to slow down the process of leaf aging. Positive properties of silver nanoparticles can help increase the stress resistance of wheat plants and develop cultivars for changing climatic conditions. For applying the preparation based on silver nanoparticles, it is necessary to consider genotypic features of plants and climatic conditions; however, this study recommends the 0.5% concentration as superior for treating spring soft wheat varieties.

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