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PHYSIOLOGICAL EFFECT OF CITRATE CHELATE NANOPARTICLES ON PLANTS OF WHEAT

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Aim. Complex study on the physiological effect of citrate chelate nanoparticles of silver and copper on spring wheat plants under presowing soaking of seeds and foliar treatment of plants. **Methods.** Physiological, biochemical, biophysical, microbiological, statistical. **Results.** The data on the physiological effect of the presowing soaking of seeds in the solutions of citrate chelate nanoparticles of silver and copper on growth processes and photochemical activity of leaves in laboratory conditions have been studied, analyzed, and summarized along with the effect of foliar treatment of spring wheat plants using the solutions of nanoparticles, and simulated phytoplasma (*Acholeplasma laidlawii var. granulum* st. 118) on the elements of the performance of spring wheat plants in field conditions. It was demonstrated that there was a considerable stimulating effect of presowing soaking of wheat seeds in 0.5 % and 1 % solutions of nanocomposites on the growth of leaves and mass accumulation of 6–7-day old sprouts. A considerable increase in the photochemical activity of the leaves of 7-day-old sprouts was found after presowing soaking in 0.5 % and 1 % solutions of nanocomposites which is in good agreement with the activation of growth processes. The negative effect of phytopathogens on the elements of grain productivity, fullness of grain in particular, was reduced in filed conditions when wheat plants were infected and then treated with nanocomposites, though there was a weak phytotoxic effect of foliar treatment of intact plants with 1 % solution. **Conclusions.** A considerable stimulating physiological effect on the growth of leaves and mass accumulation of 6–7-day-old sprouts was established after the presowing soaking of spring wheat plants in 1 % and 0.5 % solutions of citrate chelate nanoparticles of silver and copper. The increase in photochemical activity was noted in the leaves of 7-day-old wheat plants in these conditions, namely, the increase in photochemistry efficiency PSII, considerable decrease in stationary fluorescence and considerable – almost triple – increase in the value of induction coefficient Ki (correlating with the activity of ribulose biphosphate carboxylase (RuBPco)) which testifies to the increase in the intensity of photosynthetic processes in the leaf apparatus of juvenile wheat plants. The field experiment established that infecting wheat plants with phytoplasma (*A. laidlawii*) resulted in the reduction of the grain productivity indices: the weight of 1,000 grains and grain productivity in g/plant – by 14.6 and 35.5 % respectively, whereas treating with 1 % solution of silver and copper nanocomposites inhibited this process to some extent, promoting the increase in these parameters almost to the control level. The treatment of infected plants with nanoparticles led to a notable increase in the percentage of full grains. There was a weak phytotoxic effect after foliar treatment of intact wheat plants using nanocomposite solution.

Keywords: *Triticum aestivum L., Acholeplasma laidlawii var. granulum* st 118, silver and copper nanoparticles, presowing soaking of seeds, foliar treatment of plants, photosynthetic apparatus, chlorophyll fluorescence induction, grain productivity.

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INTRODUCTION

Important trends of solving the problems of modern agrobusiness, in particular, increasing the resistance and productivity of agricultural crops with simultaneous preservation of the balance of agroecosystem constituents are presented by the studies on ecologically safe and economically profitable ways of simulating the resistance of cultivated crops, for instance, such a strategically relevant crop as wheat, to phytopathogenic microorganisms. During 2007–2013, the share of wheat export in the world market of cereals was 5 % on average [1]. It should be noted that wheat is a leading culture both in Ukraine and the whole world, where our country is ranked the sixth among grain exporters [2].

However, considering a great number of niches for ecological survival of phytopathogens and their considerable mutational variability [3], the protection of fields from diseases requires a number of measures and their constant improvement [4].

A promising modern method to be implemented in different spheres, including agriculture, is the elaboration and application of novel technologies, using nanoparticles and their derivatives (based on salts of citric and other food acids) [5–7]. In recent years the researchers have applied nanoparticles of silver and its derivatives widely in industrial technologies, medicine, and even in everyday life (for instance, for disinfection). Unique properties of citrate chelate nanoparticles allowed applying them as preparations with high antiseptic qualities as well as efficient microfertilizers. Some of them are widely used as universal transmitters and agents, capable of neutralizing reactive oxygen species, in particular, superoxide anion radical, hydroxyl-radical, hydrogen peroxide. Citrate chelate nanoparticles also serve as cofactors of enzymes, taking part in oxidation-reduction reactions [6]. Due to this fact, the aspects of their ecological safety (especially regarding metal nanoparticles) and the effect on animals and plants are urgent indeed. In addition, a relevant issue in conducting monitoring studies is the investigation of toxicological properties of nanoparticles and their derivatives in the form of ionic and molecular compounds, obtained due to the interaction with pure reagents and biosphere components [6, 7].

Some of the most promising and interesting compounds, containing nanoparticles, are citrates of derivatives and biogenic metals, obtained due to modern nanotechnologies in aqueous solutions, which is the reason they are called nanoaquacitrates or citrate chelate nanoparticles [5, 6]. At the first stage, the method of electro-impulse ablation is used to obtain aquacomplexes of dispersing metals, and at the second – the direct interaction of these highly active substances with citric acid or another organic acid yields their citrates (carboxylates). This method of synthesizing citrates of metals is much cheaper than the chemical one, which allows obtaining the products of required purity in the form of aqueous solutions. Their concentrations fluctuate in a wide range depending on the parameters of the technological process. It should be noted that the application of nanotechnologies at the primary stage of obtaining citrate chelate nanoparticles allows ensuring their high purity without any secondary admixtures, as traditional chemical reactions are not used. The final product contains no nanoparticles either, as immediately after their obtaining they start a reaction with pure food acids, in particular, citric acid. The use of deionized water and especially pure metals is the warranty of their ecological and biological safety [8].

Complex studies proved their antiviral, fungicidal activity, etc., and the effect of their application in forest sericulture was demonstrated [5]. The additional advantage of the possibility of using them in agriculture is their ecological safety and economic profitability.

It is known that both silver nanoparticles and their ions are efficient against pathogenic microorganisms, but contrary to antibiotics they are of selective effect, not harming the cells of a host plant. The principle of action of these nanoparticles is based on blocking oxidation-reduction ability. In addition, the application of silver nanoparticles does not promote mutagenic variability of pathogens, thus, their application may be a part of technologies, protecting cultivated crops from pathogenic microorganisms. Copper is also widely used in the cultivation of plants to fight pathogenic microorganisms [9].

The study on the effect of the composite of citrate chelate nanoparticles Cu and Ag both during presowing soaking of seeds and foliar treatment may allow creating the prerequisites for the elaboration of methodological approaches for the creation of elements of new technologies of protecting plants, which would allow minimizing the yield loss in the conditions of development and spreading of phytopathogenic microorganisms, including phytoplasmas.

MATERIALS AND METHODS

In laboratory conditions, the seeds of spring wheat plants (*Triticum aestivum* L.), Pecherianka variety, were soaked in Petri dishes in three repeats. Presowing soaking of seeds in the solution of nanoparticle composite was conducted using the following scheme: 1 – water; 2 – presowing soaking in 0.5 % solution of the composite of silver and copper nanoparticles; 3 – presowing soaking in 1 % solution of the composite of silver and copper nanoparticles. The initial solution, called "Sumerian Silver": silver citrate with the concentration of active silver 250+25 mg/l, copper citrate – 250+25 mg/l, Nanomaterials and nanotechnologies LLC, Ukraine.

The physiological effect (E_{phy}) of nanoparticles was calculated by the change in mass accumulation (the length of leaves) of 6–7-day-old sprouts using the formula:

$$E_{phy} = \frac{M_0 - M_x}{M_x} \quad 100,$$

where M_0 – average mass of the control plant, and M_x – average mass of a plant, cultivated at the action of a certain agent. The physiological effect was considered to be of stimulating nature, if E_{phy} <0 and of inhibiting nature, if E_{phy}>0. The effect was considered reliable if $E_{phy} \geq 20\%$.

A separate laboratory experiment was conducted on the effect of the solution of nanoparticle composite on the growth of phytoplasma colonies, using the standard method of serial dilutions.

In field conditions wheat was cultivated on experimental plots of the D. K. Zabolotny Institute of Microbiology and Virology, with the total area of 70 sq.m., turf-podzolic soil. The studies were conducted on the background without any fertilizers. According to the data of the Ukrainian Hydrometeorological Center of Kyiv, during the vegetative period in 2015 weather conditions were within the norm limits compared to the average perennial conditions, rising insignificantly by 1.0–0.8 °C in May-April, whereas in June and July the average air temperatures exceeded the norm by 2.2–2.6 °C respectively. The most important and limiting index in the formation of the productivity of spring wheat fields is precipitation, the distribution of which in 2015 was rather uneven. In April, the minimal amount of precipitation was lower than the norm by 44 mm respectively. It should be noted that the period of the most intense vegetation of plants turned out to be rather dry, in particular, June and July were characterized by humidity, lower than the norm in this index, – by 60 and 36 mm respectively.

The agent of pale-green dwarf of wheat *A. laidlawii var. granulum* st. 118 (UCM BM-34) was obtained from the Ukrainian Collection of Microorganisms at the D. K. Zabolotny Institute of Microbiology and Virology, NAS of Ukraine. The artificial inoculation with the agent was conducted by Klement's method (subepidermal injection) using spring wheat plants in the tillering phase. Nine days after the injection in the field conditions, the experimental variants were treated with 1 % solution of Ag+Cu nanoparticle composite using the following experiment scheme: 1 − control (non-infected wheat plants); 2 – non-infected wheat plants + treatment with 1 % Ag+Cu; 3 – plants, artificially infected with mycoplasma *A. laidlawii* var. *granulum* st. 118 (without any treatment); 4 – plants, artificially infected with mycoplasma *A. laidlawii* var. *granulum* st. 118 + treatment with 1 % solution of Ag+Cu nanoparticle composite.

The photochemical activity of leaves was investigated by the biophysical method of chlorophyll a fluorescence induction (FI) using the portable device Floratest, designed at the V. M. Hlushkov Institute of Cybernetics, NAS of Ukraine [10]. The assessment of FI in the field conditions was conducted using the flag leaves in the blossoming phase. Dark adaptation prior to the assessment was 20 min. The experiment had five repeats. The microphotographs of healthy and infected seeds of wheat were made in the phase of complete ripeness and registered using the digital camera, Brasser MikrOkular VGA 640×480 (Germany), installed into the microscope eyepiece MBS-1 with 16× magnification.

The digital database, obtained after the series of assessments, was transmitted to the PC; Excel program was used to calculate the arithmetic mean for five measurements in each variant. The data obtained was used to build a curve of temporal dependence of the chlorophyll fluorescence intensity (CFI) which has a remarkable form of the curve with one or several maxima and has the name of CFI curve (or Kautsky curve) [11–14]. The form of this curve (Fig. 1) is rather sensitive to the changes in the photosynthetic apparatus of plants during the adaptation to different environmental conditions which served as a foundation for wide application of Kautsky effect in the study of photosynthesis [15–20].

It is known that some segments of the curve of chlorophyll fluorescence induction are indicators of respective physiological processes in the photosynthesis chain [11, 13, 14, 18–20]. It should be noted that the segment of the curve from the zero point to P reflects the efficiency of the course of "a rapid fluorescence phase", and from P to T – "dark" or slow one [13, 14]. The obtained digital database was calculated and presented in the graphic form. The following critical parameters of CFI curve were calculated: background fluorescence (F_0); F_m – fluorescence maximum at closed centers; F_t – stationary level of fluorescence; K_{pl} – amount of Q_B – non-restorable complexes, not participating in the linear transportation of electrons ($K_{pl} = (F_{pl} - F_0)/(F_m - F_0)$;

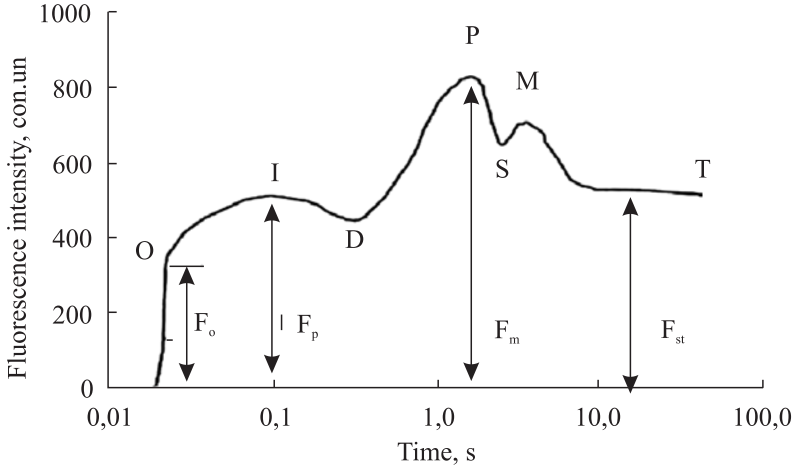


Fig. 1. Typical curve of chlorophyll fluorescence induction, Kautsky curve [13]

induction coefficient ($K_i = (F_m - F_t)/F$), correlating with the activity of ribulose biphosphate carboxylase (RuBPco, the main enzyme of Calvin cycle) [13].

The calculations of these experiments were done using Excel electronic tables. The statistical analysis was made using Statistica 8.0.

RESULTS OF INVESTIGATIONS

The investigations of the effect of presowing soaking of wheat seeds in the solutions of nanoaquacitrates of silver and copper revealed the increase in the sprouting energy by 16 % when soaking in the 0.5 % solution. At the same time, a considerable stimulating physiological effect of presowing soaking of seeds in 0.5 and 1 % solution of citrate chelate composite of silver and copper nanoparticles on the growth of leaves of 6 and 7-day-old sprouts was established (Table). The physiological effect of presowing soaking of seeds on mass accumulation of 7-day-old sprouts was higher while using 1 % concentration of citrate chelate nanoparticles – 23 %, whereas the application of 0.5 % solution promoted weak stimulating effect – 12 % (Table).

The method of chlorophyll a fluorescence induction was used to determine critical fluorescent parameters of induction curves which reflected the changes in the course of both light and dark phases of photosynthesis.

We established considerable inhibition of the background fluorescence when treated with 1 % solution of nanoparticle composite – by 22.7 % and the tendency towards its decrease at the effect of 0.5 % solution (Fig. 2 a). It is noteworthy that the background fluorescence or primary fluorescence is at the initial stage of the light phase of photosynthesis, when all the antenna centers

The physiological effect of aquachelates of silver and copper nanoparticles on spring wheat plants

Variant of presowing soaking	E_{phy} by the length of leaves, %	Test-reaction	E_{phy} by the mass of plants, %	Test-reaction
6-day-old sprouts				
Control (water)	–	–	–	–
1 % solution of Ag+Cu	27	stimulation*	–	–
0.5 % solution of Ag+Cu	25	stimulation*	–	–
7-day-old sprouts				
Control (water)	–	–	–	–
1 % solution of Ag+Cu	28	stimulation*	23	stimulation*
0.5 % solution of Ag+Cu	26	stimulation*	12	weak stimulation

Note: * – considerable phytotoxic effect.

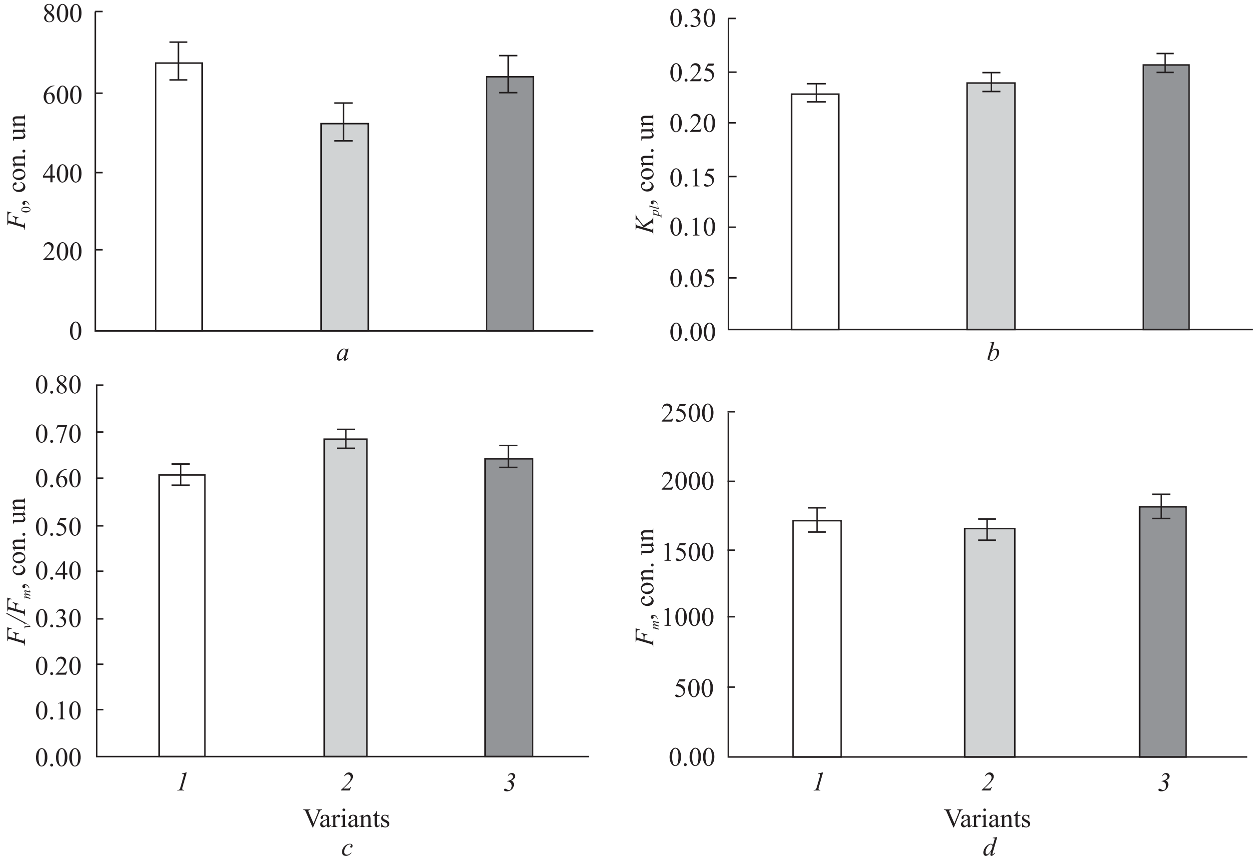


Fig. 2. Fluorescent parameters of the light phase of photosynthesis *a* – F_0; *b* – K_{pl}; *c* – F_v/F_m; *d* – F_m of 7-day-old sprouts of spring wheat at the effect of citrate chelate nanoparticles of silver and copper (variants: *1* – control; *2* – soaking seeds in 0.5 % solution of Ag+Cu; *3* – soaking seeds in 1 % solution of Ag+Cu)

are open and maximum of light energy gets to the photosynthetic apparatus. In normal conditions, its value is about 3 %, and its changes reflect the functional state of chlorophyll molecules, their inclusion into pigment-protein complexes [14–16, 20].

The decrease in background fluorescence at the effect of nanoparticle composite, revealed by us, may testify to the increase in the content of functional chlorophyll.

The efficiency of transmitting the energy of involved light quanta along the electron transfer chain (ETC) is manifested in the increase in coefficient K_{pl}, which is also a stress marker and reflects the number of so called Q_B-non-restorable complexes, which do not participate in the linear transfer of electrons along ETC [11, 13]. There is some increase in K_{pl} at the action of nanoparticles, in particular, while treating with 0.5 % solution of the composite (Fig. 2, *b*). Quantum efficiency of PSII photochemistry is reflected in the F_v/F_m index, the value of which is used to estimate the saturation of the photosynthetic apparatus with photochemically active centers [11, 14]. There is a notable increase in this value at the effect of 1 % composite – by 12.7 and 6.2% (0.5 % solution).

The value of F_m or fluorescence maximum (specific for closed centers) at the effect of 1 % solution had a tendency towards decreasing, and that of 0.5 % solution – towards increasing (Fig. 2, *d*).

The determination of parameters of slow or dark phase of fluorescence K_i and F_t reflected the positive impact of nanoparticle composite in both concentrations. For instance, parameter K_i, correlating with the activity of the main enzyme of Calvin cycle (RuBPco) increased almost thrice (Fig. 3, *a*). The value of stationary fluorescence decreased considerably in the variants of soaking in the composites of silver and copper nanoparticles (Fig. 3, *b*).

Such changes in the abovementioned parameters characterize the increase in the efficiency of dark processes of carbon fixation which are in good agreement with the abovementioned data, obtained by us, regarding the stimulating physiological effect of presowing

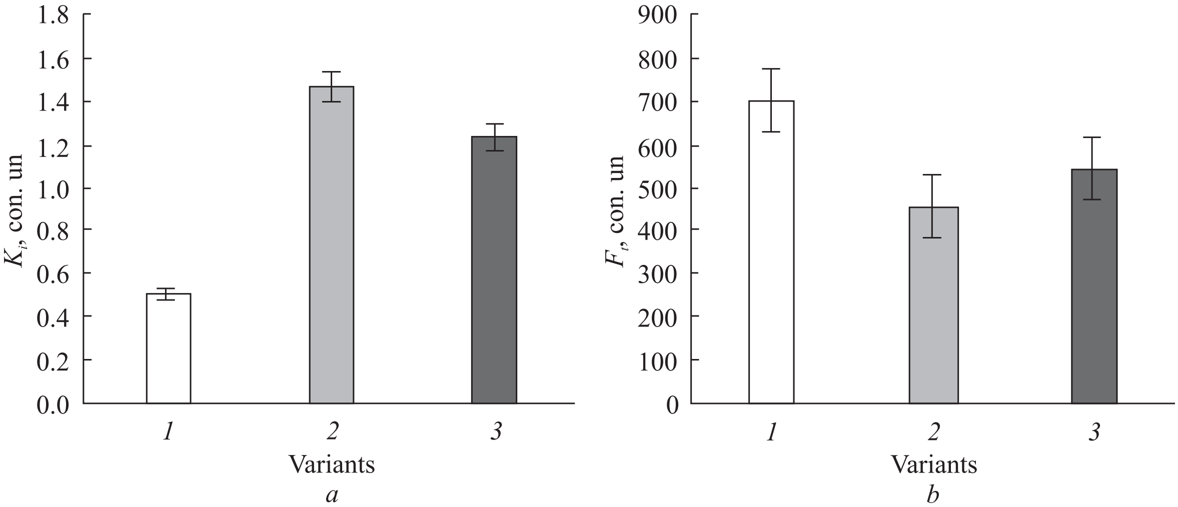


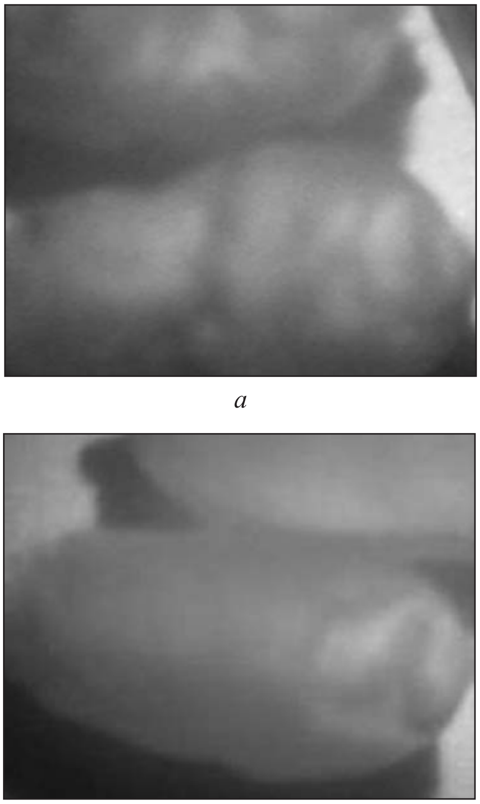
Fig. 3. Fluorescent parameters of the slow phase: *a* – K_i; *b* – F_t of 7-day-old spring wheat sprouts at the effect of the composites of silver and copper nanoparticles (variants: *1* – control; *2* – soaking seeds in 0.5 % solution of Ag+Cu; *3* – soaking seeds in 1 % solution of Ag+Cu)

soaking on the growth of leaves and mass accumulation in 6–7-day-old spring wheat sprouts.

In field conditions, the analysis of the impact of artificial infecting with phytoplasma on the productivity of plants demonstrated the inhibition of the stem height and the number of spikelets in the main spike, whereas treating with the solution of the nanoparticle composite eliminated the inhibiting effect of the agent on the growth processes of spring wheat, Pecherianka variety. However, treatment with the solution of nanoparticles in 1 % concentration had a weak phytotoxic effect on intact plants, as the impact of nanoparticles led to the decrease in the number of grains in the main spike by 14.3 %. At the same time, infecting with phytoplasma inhibited this index more considerably – by 28.6 %. The infection with phytoplasma was also remarkable for the decrease in such a relevant productivity parameter of wheat plants as the mass of 1,000 grains, the weight of which decreased by 14.6 %, whereas the treatment with 1 % solution of the composite of Ag and Cu nanoparticles eliminated the negative effect of infection, increasing the mass of 1,000 grains almost up to the control level. No considerable impact on the mass of 1,000 grains was noted when treating intact plants with the solution of nanoparticle composite. The analysis of grain productivity as per g of grain/plant demonstrated a similar tendency: the decrease in the mass of grains of infected plants by 35.5 % and the increase in this index compared to infected plants by 24.1 % (which is 20 % below the control) at the effect of the solution of nanoparticle composite.

Thus, the effect of foliar treatment with the solution of nanoparticles in the given concentration (1 % of the working solution) had a weak phytotoxic impact on intact plants, whereas when the infected plants were treated with nanoparticles, the productivity indices were below the control, but above the indices for the leaves of the infected plants without any treatment. Such ambiguous effect of foliar treatment with the relevant concentration of nanoparticles on the growth processes is explained, on the one hand, by weak phytotoxic effect of 1 % solution of nanoaquacitrates Ag and Cu on plants, and on the other – by eliminating the negative action of phytopathogens via inhibiting the growth of their colonies and terminating their destructive action on plants. These data were quite confirmed by laboratory investigations, where the development of phytoplasma – *Acholeplasma laidlawii var. granulum* strain 118 – was inhibited considerably at the effect of nanoparticles in this concentration of the solution of nanoaquacitrates Ag and Cu (1 %).

The increase in the percentage of full grains, when infected plants were treated with nanoparticle composite, was also one of the agents, reflecting the increase in productivity. The external view of the seeds of infected plants and the ones, both infected and treated with nanocomposite, is presented in Fig. 4. It should be noted that weak phytotoxic impact at foliar treatment of wheat plants using aquacitrates of silver and copper nanoparticles in 1 % concentration on productivity may be eliminated by the decrease in the solution concentration.



a

b

Fig. 4. Microphotographs of the seeds of spring wheat, Pecherianka variety, (the phase of complete ripeness), infected with *A. laidlawii var. granulum* st. 118 (*a*) and treated with the solution of the composite of nanoparticles Ag and Cu (*b*) after artificial infection

At the same time, the presowing soaking of the seeds of spring wheat in 1 % solution of citrate chelate nanoparticles of silver and copper demonstrated higher stimulating physiological effect than in 0.5 % both in the indices of the growth of leaves and mass accumulation of 6-7-day-old sprouts. This physiological action was in agreement with the increase in photochemical activity of leaves.

CONCLUSIONS

Thus, a considerable stimulating physiological effect on the growth of leaves and mass accumulation of 6–7-day-old sprouts was established after the presowing soaking of spring wheat plants in 1 % and 0.5 % solutions of citrate chelate nanoparticles of silver and copper.

The presowing treatment of the seeds with solutions of citrate chelate nanoparticles in the leaves of 7-day-old wheat sprouts resulted in the increase in photochemistry efficiency PSII, considerable decrease in stationary fluorescence and considerable – almost triple – increase in the value of induction coefficient Ki (correlating with the activity of RuBPco) which testifies to the increase in the intensity of photosynthetic processes in the leaf apparatus of juvenile wheat plants.

The field experiment was used to establish that infecting wheat plants with phytoplasma *Acholeplasma laidlawii var. granulum* strain 118 resulted in the inhibition of the stem height, the number of spikelets in the main spike, the mass of 1,000 grains and grain productivity in g/plant – by 14.6 and 35.5 % respectively, whereas treating with 1 % solution of the composite of silver and copper nanoparticles eliminated this process to some degree, promoting the increase in these parameters almost up to the control level. At the same time, the treatment of infected plants with aquacitrates of nanoparticles led to a notable increase in the percentage of full grains. However, there was a weak phytotoxic effect after foliar treatment of wheat plants using nanoparticle composite solution.

Фізіологічна дія цитратохелатів наночастинок на рослини пшениці ярої

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Мета. Комплексне дослідження фізіологічної дії цитратохелатів наночастинок срібла і міді на рослини пшениці ярої за передпосівного замочування насіння та позакореневої обробки рослин. **Методи.** Фізіолого-біохімічні, біофізичні, мікробіологічні, статистичні. **Результати.** Досліджено, проаналізовано і узагальнено дані стосовно фізіологічного ефекту дії передпосівного замочування насіння пшениці ярої розчинами цитратохелатів наночастинок срібла і міді на ростові процеси і фотохімічну активність листків у лабораторних умовах, позакореневої обробки розчином наночастинок та в умовах штучного ураження фітоплазмою (*Acholeplasma laidlawii var. granulum* шт. 118) на елементи продуктивності рослин пшениці ярої у польових умовах. Показано суттєвий стимулюючий ефект передпосівного замочування насіння пшениці у 0,5 % і 1 % розчинах нанокомпозитів на ріст листків та накопичення маси 6–7-ми добових проростків. Виявлено суттєве підвищення фотохімічної активності листків 7-ми добових проростків за передпосівного замочування у 0,5 % і 1%

розчинах нанокомпозитів, що цілком узгоджується із активацією ростових процесів. В польових умовах, за інфікування рослин пшениці та обробки нанокомпозитом зменшувалася негативна дія фітопатогенів на елементи зернової продуктивності, зокрема виповненість зерен, хоча спостерігався слабкий фітотоксичний ефект позакореневої обробки 1 % розчином інтактних рослини. **Висновки.** Встановлено суттєвий стимулюючий фізіологічний ефект на ріст листків й накопичення маси 6–7-добових проростків за передпосівного замочування насіння пшениці ярої у 1 % і 0,5 % розчинах цитратохелатів наночастинок срібла і міді. За цих умов у листках 7-ми добових проростків пшениці відмічено зростання фотохімічної активності: зростання ефективності фотохімії ФСІІ, суттєве зниження стаціонарної флуоресценції і суттєве – майже втричі – підвищення величини індукційного коефіцієнта K_i (корелює із активністю рибулозобісфосфаткарбоксилази (РБФК), що свідчить про зростання інтенсивності фотосинтетичних процесів в листковому апараті ювенільних рослин пшениці. В умовах польового досліду виявлено, що інфікування рослин пшениці фітоплазмою (*A. laidlawii*) призводило до зниження показників зернової продуктивності: маси 1000 зерен і зернової продуктивність в г/рослину – на 14,6 і 35,5 % відповідно, тоді як обробка 1 %-ним розчином композиту наночастинок срібла і міді дещо нівелювала цей процес, сприяючи підвищенню цих параметрів майже до контрольного рівня. За обробки наночастинками інфікованих рослин відмічено підвищення відсотку виповнених зерен. За позакореневої обробки інтактних рослин пшениці розчином композиту наночастинок відмічався слабкий фітотоксичний вплив.

Ключові слова: *Triticum aestivum L., Acholeplasma laidlawii var. granulum* шт. 118, наночастинки срібла і мі-ді, передпосівне замочування насіння, позакоренева обробка рослин, фотосинтетичний апарат, індукція флуоресценції хлорофілу, зернова продуктивність.

Физиологическое действие цитратохелатов наночастиц на растения пшеницы ярой

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Цель. Комплексное исследование физиологического действия цитратохелатов наночастиц серебра и меди на растения пшеницы ярой при предпосевном замачивании семян и внекорневой обработке растений. **Методы.** Физиолого-биохимические, биофизические, микробиологические, статистические. **Результаты.** Исследованы, проанализированы и обобщены данные физиологического эффекта предпосевного замачивания семян пшеницы яровой растворами цитратохелатов наночастиц серебра и меди на ростовые процессы и фотохимическое активность листьев в лабораторных условиях и внекорневой обработки раствором наночастиц и в условиях искусственного заражения фитоплазмой (*Acholeplasma laidlawii var. granulum* шт. 118) на элементы продуктивности растений пшеницы яровой в полевых условиях. Показан существенный стимулирующий эффект предпосевного замачивания семян пшеницы в 0,5 % и 1% растворах нанокомпозитов на рост листьев и накопление массы 6–7 суточных проростков. Выявлено существенное повышение фотохимической активности листьев 7-ми дневных проростков при предпосевном замачивании в 0,5 % и 1 % растворах нанокомпозитов, что согласуется с активацией ростовых процессов. В полевых условиях, при инфицировании растений пшеницы фитоплазмой и внекорневой обработкой нанокомпозитов уменьшалось негативное воздействие фитопатогенов на элементы зерновой продуктивности, в том числе наполненность зерен, хотя наблюдался слабый фитотоксичный эффект от внекорневой обработки 1% раствором интактных растений. **Выводы.** Установлен существенный стимулирующий физиологический эффект на рост листьев и накопление массы 6–7-суточных проростков при предпосевном замачивании семян пшеницы яровой 1 % и 0,5 % раствором цитратохелатов наночастиц серебра и меди. В этих условиях в листьях 7-ми дневных проростков пшеницы отмечен рост фотохимической активности: рост эффективности фотохимии ФСII, существенное снижение стационарной флуоресценции и существенное – почти втрое – повышение величины индукционного коэффициента K_i (коррелирует с активностью РБФК), что свидетельствует о росте интенсивности фотосинтетических процессов в слоеном аппарате ювенильных растений пшеницы. В условиях полевого опыта установлено, что инфицирование растений пшеницы фитоплазмой (*A. laidlawii*) приводило к снижению показателей зерновой продуктивности: массы 1000 зерен и зерновой производительности в г/растение – на 14,6 и 35,5 % соответственно, тогда как обработка 1%-ным раствором композита наночастиц серебра и меди несколько нивелировала этот процесс, способствуя повышению этих параметров почти до контрольного уровня. Вместе с тем при обработке наночастицами инфицированных растений отмечено повышение процента заполненных зерен. Однако при внекорневой обработке интактных растений пшеницы раствором композита наночастиц отмечалось слабое фитотоксическое влияние.

Ключевые слова: *Triticum aestivum L.*, *Acholeplasma laidlawii var. granulum* шт. 118, наночастицы серебра и меди, предпосевное замачивание семян, внекорневая обработка растений, фотосинтетический аппарат, индукция флуоресценции хлорофилла, зерновая продуктивность.

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