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Nanotechnologies for increasing the productivity and quality of potatoes in a changing climate

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ABSTRACT

The objective of this study is to examine the impact of a pre-sowing treatment of potato tubers with metal nanoparticles (NPs) for plant protection against phytopathogens in a changing climate. The research was conducted over a period of three years under conditions of increasing average air temperature and decreasing rainfall, which were conducive to the development of potato diseases. The study involved the development of nanobiopreparations containing Fe, Zn, Cu, Mo, Mg, Mn, and B nanoparticles (NPs) in a polymer. Three-year observations showed that the optimal composition of the preparation contains (Zn 10-2% + Cu 10-8% + Fe 10-6% + Mo 10-8%) NPs. The potato tubers were pre-treated with NPs in polymer, resulting in a 52% decrease in the prevalence of A. solani and a 4.6-fold reduction in the degree of plant damage in 2018. In 2019, both indicators exhibited a 2-fold decrease. In 2021, a 20% decrease in the prevalence of A. solani was observed, along with a 40% reduction in the degree of plant damage when compared to the control. The pre-sowing treatment of potato tubers with NPs in the polymer composition increased crop yield and commercial tubers. The results obtained from this study indicate the practical significance of nanotechnology in potato production.

Contribution/Originality: In a pioneering development, nanobiopreparations have been engineered and evaluated for their efficacy in protecting potato crops from diseases under conditions of a changing climate. This innovative formulation comprises a blend of four nanoparticles, meticulously selected to ensure optimal concentrations for plant growth and development. These nanoparticles are embedded within a polymer matrix, which serves as a protective barrier against adverse environmental factors and prevents the nanoparticles from entering the soil, thereby ensuring environmental safety.

1. INTRODUCTION

The impact of global climate change on agriculture is a significant concern. The rise in global temperatures, changes in precipitation patterns, and increased frequency of extreme weather events, including droughts, dry spells, and floods, pose a threat to crop yields and the stability of food systems. In some regions, this has led to a reduction in the area available for farming, while in others, it has resulted in the spread of pests and diseases. In response, farmers are compelled to adapt by adopting sustainable crop varieties, water management practices, and new technologies, including advances in nanotechnology (Idrisov, 2023).

Using the no-technology, it is possible to increase the yield of such a socially important crop as potatoes. Russia annually produces 33 million tons of potatoes, which is 11% of the total annual potato yield in the world. The average yield of this crop in Russia reaches 12 t/ha, although the potential of most varieties is 4-5 times higher. One of the reasons for the low yield is the widespread occurrence of potato diseases, with annual yield loss of up to 30%. Depending on weather conditions, the level of potato disease incidence fluctuates significantly, so systematic measures for potato cultivation are constantly being improved. Special attention is paid to pre-sowing treatment of tubers, which is carried out with the help of nanobiopreparations developed by us. Interest in the use of nanoparticles (NPs) in crop production is associated with their unique properties. Our long-term studies have revealed the following features of the biological action of NPs. Nanoparticles have low toxicity, 7-50 times less toxicity than metals in ionic form; they have prolonged and polyfunctional action; they stimulate metabolic processes in biotic doses; they easily penetrate into all organs and tissues; their biological activity is associated with the structure of particles and their physicochemical characteristics; metal NPs show a synergistic effect with natural polysaccharides (Yuan et al., 2018; Zeyruk et al., 2022; Zeyruk et al., 2019). Considering these properties of NPs, our laboratory has developed preparations based on essential trace elements (Fe, Zn, Cu, Mo, Mg, Mn, B, and their compositions) introduced into polymers for pre-sowing treatment of seeds and tuber plants. To study the effect of nanoparticles on the growth and development of potato plants and their productivity, we selected essential elements: copper, boron, molybdenum, iron, zinc, manganese, and magnesium. The choice of these elements is due to their exceptional role in the formation of yield.

It is known that copper accelerates the formation of potato tubers and increases resistance to phytopathogens. In the case of copper deficiency, plants lose turgor and upper leaves, the number of productive stems decreases, and growth slows down (specify reference to literature) (Hänsch & Mendel, 2009).

Boron promotes lateral root growth, enhances starch synthesis and calcium assimilation, and increases the quality and marketability of the crop. (specify reference to literature) (Hänsch & Mendel, 2009).

Molybdenum deficiency is manifested in poor nitrogen assimilation and as a consequence, it leads to a reduced plant growth rate. Tubers grown in the context of molybdenum deficiency are characterized by low palatability and have a bitter taste (Elrys, Abdo, & Desoky, 2018; Hänsch & Mendel, 2009).

Iron is involved in the synthesis of chlorophyll, affects the activity of enzymes, and participates in electron transfer, which is necessary for photosynthesis and energy production. Iron also contributes to the formation of basic proteins and enzymes that support plant growth and development. In cases of iron deficiency, signs of inter-strand chlorosis are observed, and in cases of acute deficiency of this element, chlorosis of the entire leaf surface occurs (Potato, 2013). Zinc is part of a number of enzymes that participate in photosynthesis, respiratory processes, and redox reactions. In cases of zinc deficiency, the structure of the leaf plate changes, the structure of plant tissues is disturbed; there is a decrease in the size of chloroplasts and the concentration of mitochondria. In potatoes, the development of chlorosis is noted (Lebedeva, 2015).

Magnesium plays a major role in the processes of photosynthesis, at key stages of sugar and protein synthesis, and in the transport of sucrose from leaves to tubers. A characteristic sign of magnesium deficiency is interveinal chlorosis, which, in cases of significant deficiency, leads to twisting and brittleness of leaf plates (Koch, Naumann, Pawelzik, Gransee, & Thiel, 2020).

The aim of this study is to investigate the effect of pre-planting treatment of potato tubers with preparations containing micronutrient nanoparticles in polymer formulations on potato disease incidence, potato yield, and quality under changing climate conditions during 2018, 2019, and 2021.

2. MATERIALS AND METHODS

2.1. Physicochemical Parameters of NPs

Electroneutral iron, zinc, copper, molybdenum, magnesium, and manganese NPs were prepared by a flow-levitation method as described by Lisińska, Pęksa, Kita, Rytel, and Tajner-Czopek (2009). The Fe, Zn, Cu, Mo, Mg, Mn, and B NPs used were single-crystal structures of spherical shape with an oxide film on the surface, which was formed as a result of particle passivation with air to reduce the nanoparticle pyrophoricity. The size distribution curves were in the region of Fe NPs at 5-160 nm, Zn NPs at 5-250 nm, Cu NPs at 5-250 nm, Mo NPs at 5-150 nm, B NPs at 10-600 nm, and Mg NPs at 5-600 nm. The average diameter of Fe NPs was 56.0 ± 0.9 nm, Zn NPs -- 60.6 ± 3.7 nm, Cu NPs -- 65 ± 1.2 nm, Mo NPs -- 70 ± 2.1 nm, B NPs -- 134 ± 5.4 nm, and Mg NPs -- 193 ± 12 nm. The phase composition of NPs was as follows: the nanoscale iron powder contained the Fe-α metallic iron crystal phase - 27.9%, and the γ-Fe_3O_4 (magnetite) iron oxide crystal phase - 72.1%. The nanoscale zinc powder contained a metallic zinc crystalline phase; no oxide phases were detected by XRD analysis (however, oxide phases may be X-ray amorphous). Cu NPs had only a crystalline phase; Mo NPs included a metallic phase, 64.0 ± 4.2%, and dimolybdenum carbide, 36.0 ± 2.9%; amorphous boron NPs contained BH_3O_3, 90.1%, and B_2O, 9.9%; Mg NPs included a metallic phase, 79.0 ± 5.4%, and magnesium oxide (MgO), 21.0 ± 1.3%.

2.2. Plant Material

The present study focuses on the potato plant (Solanum tuberosum L.) variety *'Sante'*. *'Sante'* is a popular table variety, bred in the Netherlands, and is widely distributed in Europe and Russia due to its high flavor qualities and versatility of use. The variety's main characteristics are as follows: it is medium-early, resistant to phytophthora, parsha, viruses Y and A, as well as to the golden nematode. The mean tuber weight recorded was between 70 and 90 grams.

2.3. Preparation of the NPs Containing Substance

For the nanobiopreparations, an aqueous suspension of metal powders was obtained on a Scientz JY 92-IIN ultrasonic disintegrator (China) in the 0.5 A mode, at a frequency of 44 kHz for 30 seconds, with a 30-second break and ice cooling in three repetitions. The suspension was then added to a polymer solution containing 1 wt.% Na_2-carboxymethylcellulose, 2.5% polyethylene glycol-400, 0.037% Na_2-EDTA, and rhodamine 6G (0.002%), a cationic dye to visualize the uniformity of film coverage. The following preparations were prepared for the trials: №1: (Zn 10^{-2}%+ Cu 10^{-8}%+ Fe 10^{-6}%+ Mo 10^{-8}%) NPs; № 2: (Zn 10^{-4}%+ Cu 10^{-8}%+ Fe 10^{-8}%+ Mo 10^{-8}%) NPs; №3: (Cu10^{-9}%+ B10^{-6}%+ Mo 10^{-7}%+ Mg 10^{-6}%) NPs; №4: (Cu 10^{-9}%) NPs; №5: (Mn 10^{-6}%) NPs.

2.4. Field Experiments

The study of metal NPs' effects on potato yield, growth, and potato disease was carried out on the podzolic and sod-podzolic soils of the experimental field (55.679458 N, 37.996029 E, Kraskovo village, Lyubertsy district, Moscow region, Russia). The experimental fields are located in a region that is typical of the Central region of Russia. The soil of the experimental field was sod-podzolic sandy loam. The potato planting was executed by means of a clonal planter, with a row spacing width of 75 cm and a planting density of 400 pieces per 100 m² in the first decade of May in the years 2018, 2019, and 2021. The planting pattern employed was 75 x 35 cm. The experiment was repeated four times. The placement of plots was randomized. The number of plants counted in each repetition was 200. The spraying of planting tubers was conducted using the knapsack equipment 'KWAZAR', with a rate of 10 liters of working liquid per ton. The area of each plot was 25 m². In order to ascertain the prevalence of Alternaria, the number of affected plants exhibiting dry, brownish-black spots, measuring up to 1.5 cm in diameter, distributed over the entire surface of the leaf plate, was meticulously enumerated. Similarly, the prevalence of Rhizoctoniosis was determined by the presence of specific symptoms, including shingles on the lower part of the potato stem, upper leaves twisted along the vein, green air tubers formed in the shoot axils, and 'white foot', characterized by a whitish-grey film covering the lower part of the stem.

The total experimental scheme is visualized in the graphical abstract.

The prevalence of Alternaria and Rhizoctonia diseases of potato was estimated using the formula:

$P = (n \times 100)/N$, where:

P - prevalence of the disease (%); n - number of plants or tubers affected by the disease; N - number of plants or tubers in the group.

The degree of potato Alternaria was calculated using the following formula:

$R = \sum bt \times 100 / 7n$, where R is the degree of disease development (%), $\sum bt$ is the sum of products of the defeat score by the number of plants or tubers affected by this score, n is the number of plants or tubers in the sample, and 7 is the highest score of the accounting scale.

Figure 1: Scheme.

Figure 1. Scheme. Experience design.

It is imperative to note that all counts were conducted in accordance with the standard methods outlined in the following publications: 'Methods of Research on Potato Culture', 'Methods of Agrotechnical Experiments, Records, Observations, and Analyses on Potato' (Zhevora, 2021); 'Methods of Research on Potato Protection from Diseases, Pests, Weeds, and Immunity', GOST 33996-2016, 'Seed Potatoes: Technical Conditions and Methods of Quality Determination'.

Statistical processing of data was carried out in Microsoft Excel 2010, ANOVA, and Statistica 20 ('StatSoft, Inc.', USA) programs. The data were calculated as the ratio of the test values against control (Exp Contr−1, %) and analyzed by the ANOVA procedure with the Statistica 20 package. A probability level of 0.05 was considered statistically significant. The results are presented as a mean ± SD.

3. RESULTS

3.1. Meteorological Conditions of Potato Cultivation in 2018, 2019 and 2021

The mean air temperature for the growing seasons of 2018, 2019, and 2021 was 18.7°C, 17.4°C, and 19.7°C, respectively. The mean temperature for the period 2018-2021 was 16.5°C. Total rainfall, with a norm of 260.5 mm, for the growing seasons of 2018, 2019, and 2021 was 205.9 mm (79.04% of the norm), 292.3 mm (112.2% of the norm), and 258.0 mm (99.04% of the norm), respectively. The sum of effective temperatures (above 10°C) totaled in 2018 was 2318.03°C, in 2019 it was 2126°C, and in 2021 it was 2354.61°C. The hydrothermal coefficient (HTC) in 2018 was 0.89 (moisture level of the area - arid), in 2019 it was 1.39 (wet), and in 2021 it was 1.096 (slightly arid) (Table 1).

Table 1. Meteorological indicators of the growing seasons of 2018, 2019 and 2021 (According to the Korenevo weather station*).

Main indicators	Months and decades											
	May			June			July			August		
	1	2	3	1	2	3	1	2	3	1	2	3
Air temperature °C												
Multi-year averages	11.2	13.3	14.6	15.9	17.4	18.4	18.8	19.6	19.4	18.8	17.5	15.7
2018 г.	15.5	17.1	16.6	13.8	18.0	22.3	18.1	22.2	20.95	21.5	19.65	18.5
2019 г.	14.2	15.99	18.7	21.8	20.5	18.7	16.9	15.5	18.2	13.94	17.3	17.2
2021 г.	9.2	18.5	15.6	16.7	21.5	25.9	22.6	25.9	20.6	21.0	21.0	17.4
Rainfall, mm												
Multi-year averages	15.3	15.2	21.8	19.4	21.6	24.2	24.0	27.8	27.5	19.8	22.2	25.5
2018 г.	5.4	45.2	4.2	13.6	8.6	7.7	46.0	29.9	11.3	3.5	13.2	17.3
2019 г.	15.5	37.9	11.0	0.2	5.6	53.8	12.7	81.4	18.5	33.2	22.1	0.4
2021 г.	52.1	6.6	21.2	16.3	3.1	39.2	5.7	14.7	8.2	20.6	38.4	31.9
Relative humidity of the air, %												
Multi-year averages	71.0	74.0	75.0	81.0	81.0	80.0	80.0	80.0	82.0	80.0	85.0	86.0
2018 г.	67.1	71.2	61.3	65.98	65.8	61.5	79.6	81.7	82.85	70.65	72.4	70.0
2019 г.	72.7	65.1	64.8	55.0	62.6	71.6	70.2	88.1	79.2	85.1	87.3	76.8
2021 г.	75.9	69.9	67.0	76.7	76.2	80.8	75.9	70.6	75.1	85.6	85.1	84.8
Hydrothermal coefficient												
Multi-year averages	1.1-1.3											
2018 г.	0.35	2.8	0.23	1.15	0.48	0.35	2.54	1.35	0.51	0.16	0.67	0.85
2019 г.	1.24	2.37	0.54	0.01	0.27	2.88	0.75	5.24	0.92	2.38	1.28	0.02
2021 г.	11.8	0.36	1.31	0.98	0.14	1.52	0.25	0.57	0.36	0.98	1.83	1.67

***Note:** Measurements were carried out daily. Multiyear averages were calculated for all years of observations at the meteorological station (1955-2017).

The development of potato diseases is significantly impacted by a complex of meteorological factors, including indicators such as temperature, air and soil humidity, the sum of effective temperatures, and the amount of rainfall. Table 2 presents data on the influence of agrometeorological conditions on the spread of potato Alternaria disease incidence (Table 2).

Table 2. Meteorological indicators of vegetation periods 2018-2021 (According to the weather station 'Korenevo', Lyuberetsky District, Moscow Region) and the prevalence of Alternaria (X ± SEM).

Year	Prevalence of Alternaria solani S.		The mean daily air temperature for the vegetation period is defined as C°± to mean annual (16.5°C).	Rainfall totals, Mm ± to the mean annual (260.5 mm)	Hydrothermal coefficient (HTC)
	%	Nature			
2018	78.8± 8.1	E	+ 2.2	-54.6	0.89
2019	31.2±3.3	M	+ 0.9	+31.8	1.39
2020	58.8±6.1	M-E	+ 0.6	+166.6	2.1
2021	100	E	+ 3.2	-2.5	1.1

***Note:** E - epiphytotic (Disease development in more than 50% of plants); M - moderate development (25-50%); n (Number of plants) = 200 for each year.

The research findings indicated a substantial increase in air temperature compared to the mean annual values, exhibiting a consistent direction across the Central Non-Chernozem region. During the growing season, the average increase ranged from +0.6 to +3.2°C (see Table 2).

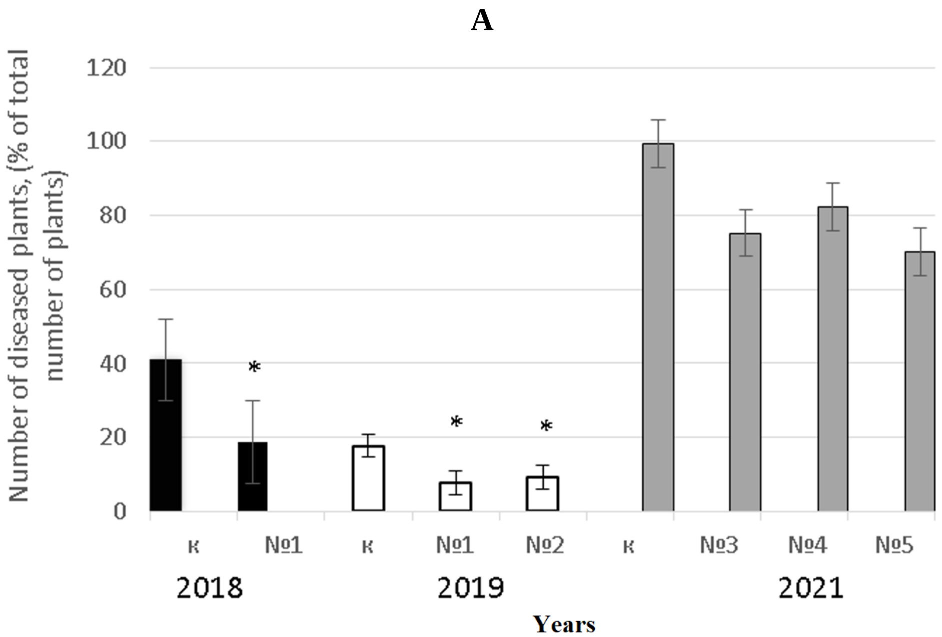
The months of May 2018, June 2021, and July 2021 were identified as the warmest on record, with temperatures of +3.4°C, +3.2°C, and +3.8°C, respectively. In 2018 and 2021, the temperatures in August were observed to exceed the average by 2.5-2.6°C. The sum of effective temperatures (SAT) for the growing season showed an excess over the annual average from 254.24°C in 2020 to 628.81°C in 2021.

Rainfall has been identified as a favorable factor for the development of potato plants and pathogens. May 2018 exhibited a 4.8% increase compared to the standard, with 52.3 mm of precipitation recorded. In contrast, 2020 was marked by the highest precipitation levels, with an increase of 117.0%. Conversely, the least rainfall was observed in June 2018 (-35.3 mm) and July 2021 (36.1% of the mean - 79.3 mm), and in August 2018 and 2020 (50.4-54.1%). Conversely, the highest rainfall levels were observed in June 2020 (25.4 mm), in July 2020 (151.7% of the standard deviation), and in August 2021 (134.7%). It is evident that relative air humidity exerts a substantial influence on the initial infection of leaf diseases. Concurrently with air temperature, it functions as a factor that imposes limitations on the progression of these diseases. The lowest recorded value of relative air humidity during the growing season was observed in 2018. This is characterized by a relative humidity of 70.9%, categorized as air drought. Such agrometeorological conditions during the 2018 growing season were generally unfavorable for the growth, development, and productivity of potatoes, but they promoted the development of Alternaria and cold weather in late May and early summer 2018 and rhizoctoniosis.

Conversely, the agrometeorological conditions during the 2019 growing season were conducive to potato growth, development, and productivity, while also being conducive to the development of rhizoctoniosis. The 2021 growing season was characterized by unfavorable conditions for potato growth, development, and productivity, while also being conducive to the development of Alternaria.

3.2. The Effect of NPs in the Polymer Coating on the Prevalence and Extent of Lesions by Alternaria solani S. and the Prevalence of Rhizoctonia solani K.

In 2018, the composition (Zn 10^{-2}%+Cu 10^{-8}%+Fe $10^{-6\%}$+Mo 10^{-8}%) NPs - preparation No. 1 was used for potato tubers presowing treatment. It was shown that tubers presowing treatment with this preparation reduced the prevalence of *A. solani* by 52%, and the degree of plant damage by 2.5 times compared to the control. In 2019, preparation No. 1 confirmed its properties to reduce the prevalence and degree of plant Alternaria damage. Preparation No. 2 reduced these indicators by two times compared to the control. In 2021, three nanobiopreparations containing the composition (Cu10^{-9}%+ B10^{-6}% + Mo 10^{-7}%+ Mg 10^{-6}%) NPs, Cu NPs 10^{-9}%, Mn NPs 10^{-6}% were tested. Using of preparation No. 3, No.4 and , and No.5 decrease the prevalence of *A. solani* by 30%, 20%, 40% respectively and the degree of plant damage by 80%, 60%, 90% compared to the control, respectively (Figure 2 A,B).



B

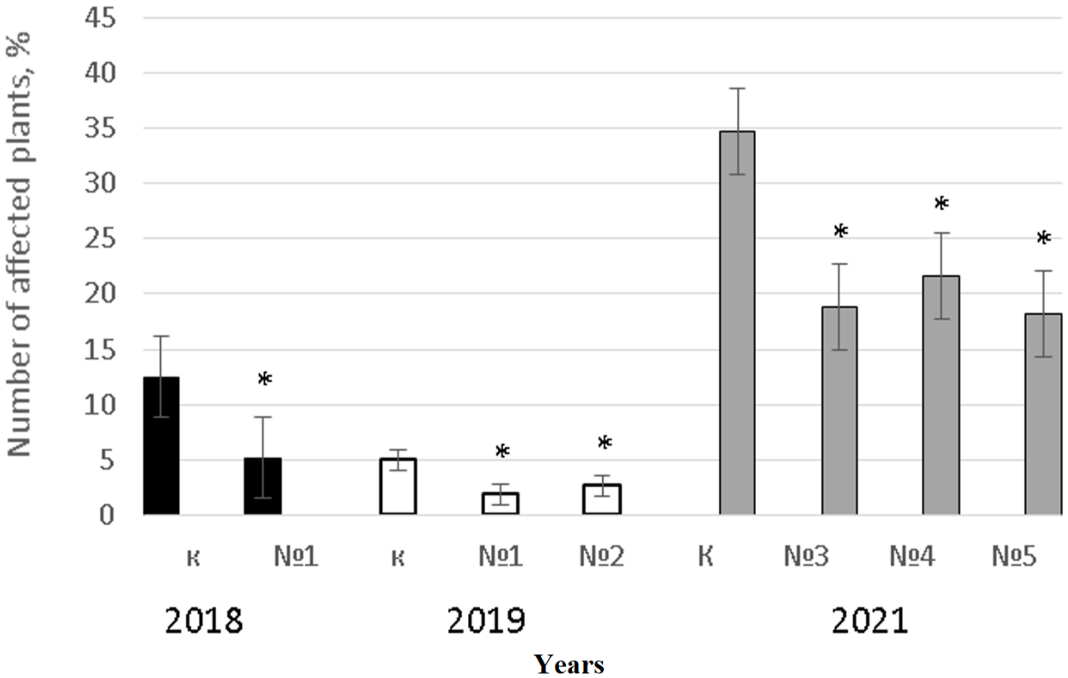


Figure 2. Prevalence (A) and degree of plant damage (B) by *Alternaria Solani* S. after presowing treatment of potato tubers with the nanopreparations (polymer coating containing NPs). N=200 plants.

Note: * - indicate significant differences ($p \leq 0.05$).

In the study of *R.solani* prevalence, it was shown that pre-planting treatment with composition (Zn 10^{-2}% + Cu 10^{-8}%+ Fe 10^{-6}%+Mo 10^{-8}%) NPs - preparation No 1 reduced the prevalence by 15% in 2018 and almost by 3 times in 2019. Composition (Zn 10^{-4}%+ Cu 10^{-8}%+ Fe 10^{-8}%+ Mo 10^{-8}%) NPs - preparation No 2 reduced the *R. solani* prevalence by 3-fold compared to the control. In 2021, pre-planting treatment of potato tubers with preparations No. 3, 4, 5 reduced the prevalence of *R. solani* by 2 times, 4 times and by 20% compared to the control, respectively (Figure 3).

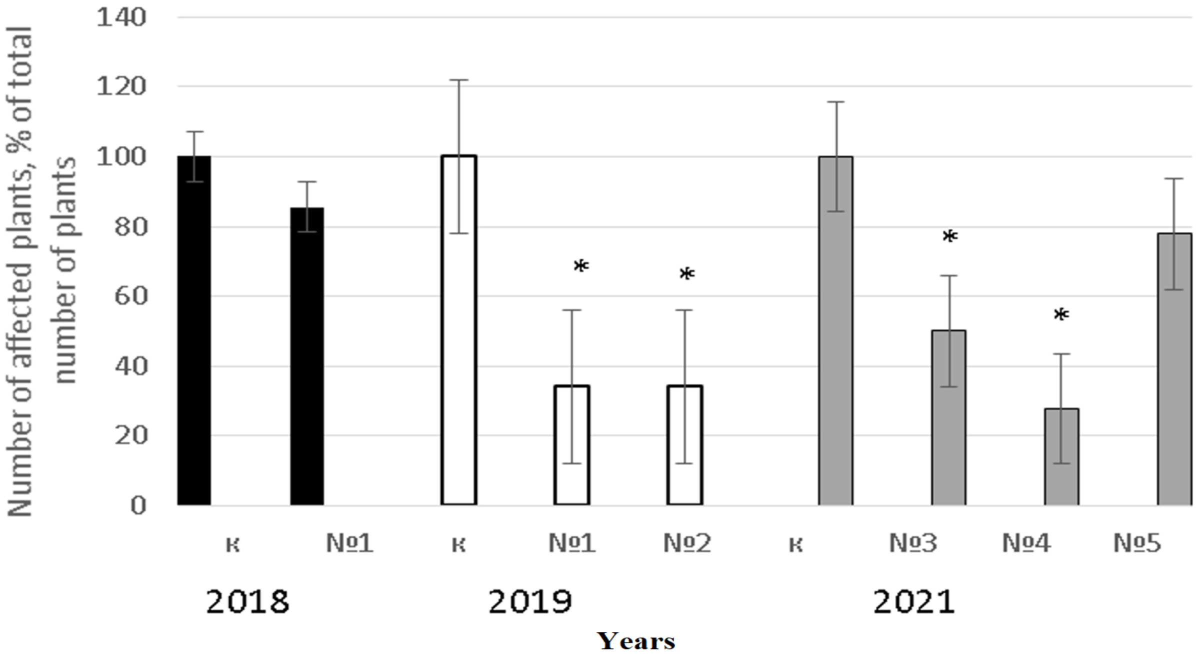


Figure 3. Prevalence by *Rhizoctonia solani* K. after presowing treatment of potato tubers with the nanobiopreparations (polymer coating containing NPs).

Note: N=200 plants. * - indicate significant differences ($p \leq 0.05$).

3.3. Field Tests of NPs' Different Composition in the Polymer Coating on Potato Yield

The following tables present the data on the effect of the pre-planting treatment on potato productivity and potato harvest quality: Table 3 and Table 4. It is evident that in 2018, despite the backdrop of a diminished yield in the control group, the pre-planting treatment employing preparation No. 1 resulted in a notable augmentation in yield, amounting to 25.7%, including an increase in marketable tubers by 11.7% in comparison to the control. By fractional composition, tubers measuring between 30 and 60 mm dominated, with a total of 2.6 t/ha, which is notably higher than the control group. In 2019, the pre-planting treatment of potatoes with preparations No. 1 and No. 2 resulted in a 28.1% and 21.3% increase in yield, respectively, including a 31.2% and 24.4% increase in marketable tubers compared to the control. In terms of fractional composition, tubers measuring over 60 mm dominated, with yields of 3.8 t/ha and 6.5 t/ha, respectively, surpassing the control. The yield in 2021 at the pre-planting treatment with preparations No. 3 and No. 4 was 3.6% and 3.3% higher, respectively, than the control, including marketable tubers by 1.5% and 2.9%. By fractional composition, tubers measuring between 30-60 mm prevailed (Table 3).

Table 3. The effect of NPs with different compositions in the polymer coating on potato productivity*.

Years	Treatment	Tuber yield				Tuber size class yield, t/ha		
		Total		including marketable tubers				
		t/ha	Exp contr^{-1}, %	t/ha	Exp contr^{-1}, %	30-60 mm	> 60 mm	< 30 mm
2018	Control	13.2^{a}±0.8	100	12.0^{a}±0.5	100	10.9^{a}±0.5	1.1^{a}±0.4	1.2^{a}±0.3
	No.1	16.5 ^{ab}±1.1	125.7	13.4^{ab}±0.7	111.7	12.6^{ab}±0.5	0.8^{a}±0.2	3.0^{ab}±1.2
2019	Control	23.5^{b}±1.8	100	22.1^{b}±1.1	100	44.0^{c}±1.4	50.0^{d}±10.4	6.0^{c}±2.3
	No.1	30.1^{bc}±2.5	128.1	29.0^{bc}±1.5	131.2	42.5^{cd}±1.5	53.8^{d}±11.5	3.7^{b}±1.1
	No.	28.5^{bc}±1.1	121.3	27.5^{bc}±1.3	124.4	40.1^{cd}±0.9	56.5^{d}±10.5	3.4^{b}±0.9
2021	Control	15.1^{a}±0.7	100	13.6^{a}±0.6	100	10.4^{a}±0.3	80.0^{cd}±14.7	9.6^{d}±2.4
	No.3	15.6^{a}±0.5	103.6	13.8^{a}±0.5	101.5	79.0^{cd}±11.4	80.7^{cd} ±13.6	11.4^{dc}±2.0
	No.4	15.6^{a}±0.6	103.3	14.0^{ab}±0.6	102.9	10.6^{a}±0.4	79.7^{cd}±11.3	9.7^{d}±1.9
	No.5	14.9^{a}±0.7	98.9	13.4^{ab}±0.7	98.5	13.3^{ab}±0.5	76.9^{cd} ±10.5	9.8^{d}±1.5

Note: No. 1: (Zn 10^{-2}%+%+ Cu 10^{-8}%+ Fe 10^{-6}%+ Mo 10^{-8}%) NPs; No.2: (Zn 10^{-4}%+ Cu 10^{-8}%+ Fe 10^{-8}%+ Mo 10^{-8}%) NPs; No. 3: (Cu10^{-9}%+ B10^{-6}% + Mo 10^{-7}%+ Mg 10^{-6}%) NPs; No. Cu10^{-9}% NPs; No.Mn 10^{-6}% NPs. Different letters in rows indicate significant differences ($p \leq 0.05$).
*a, b, c and d show that the obtained differences between the experimental and control groups are significant, p is less than or equal to 0.05.

Table 4. The effect of NPs with different compositions in the polymer coating on the potato crop characteristics *.

Years	Treatment	Injured tubers, %					Yield of marketable tubers	
		All tubers	Phytophthora	Dry rot	Rhizoctonia	Common scab	t/ha	Exp contr^{-1}, %
2018	Control	9.3^{a}	0	1.3^{a}	0	8.0^{a}	10.9^{a}±1.1	100
	№1	4.2^{c}	0	1.4^{a}	0	2.8^{c}	12.8^{a}±1.4	117.4
2019	Control	9.3^{a}	0.2	1.4^{a}	0	1.3^{d}	21.5^{c}±1.6	100
	№1	1.3^{cd}	0.3	1.0^{b}	0	0	28.6^{c}±1.7	133.0
	№2	1.9^{d}	0.3	1.6^{ab}	0	0	27.0^{c}±1.5	125.6
2021	Control	9.3^{a}	0	3.5^{b}	0.3	1.3	12.9^{ab}±0,9	100
	№3	1.2^{cd}	0	1.2^{bc}	0	0	13.6^{ab}±1.3	105.4
	№4	2.0^{d}	0	2.0^{bc}	0	0	13,7^{ab}±1.3	106.2
	№5	3,2^{d}	0	1,3	0.3	1,5	3,0	100.8

Note: No. 1: (Zn 10^{-2}%+%+Cu 10^{-8}%+Fe 10^{-6}%+Mo 10^{-8}%) NPs; No. 2: (Zn 10^{-4}%+Cu 10^{-8}%+Fe 10^{-8}%+Mo 10^{-8}%) NPs; No. 3: (Cu10^{-9}%+ B10^{-6}% + Mo 10^{-7}%+ Mg 10^{-6}%) NPs; No. 4: Cu10^{-9}% NPs; No. 5: Mn 10^{-6}% NPs. Different letters in rows indicate significant differences ($P \leq 0.05$).
*a, b, c and d show that the obtained differences between the experimental and control groups are significant, p is less than or equal to 0.05.

In 2018, the potato harvest quality post-tube pre-sowing with preparation No. 1 exhibited a 2.2-fold reduction in the total number of diseased tubers, along with a 2.86-fold increase in susceptibility to common parsha compared to the control. In 2019, the efficacy of preparation No. 1 in reducing the total number of diseased tubers was confirmed, with a recorded decrease of 2.2 times. In 2021, preparations No. 3, No. 4, and No. 5 were employed, with the number of diseased tubers being reduced by 4.3 times, 2.6 times, and 1.6 times, respectively, compared to the control. Concurrently, the yield of standard potatoes (2018 and 2019) when treated with preparation No. 1 was 11.7% and 33% higher than the control. Furthermore, the application of preparation No. 2 (2019) resulted in a 25% increase in yield, while preparations No. 3 and No. 4 (2021) increased the yield of standard potatoes by 5.4% and 6.2%, respectively (Table 4).

4. DISCUSSION

In the context of any program or forecast document pertaining to the prospects and outcomes of agricultural development, weather conditions are recognized as the primary factor influencing the sector. In recent years, there has been an increase in the number of weather hazards in comparison with those recorded thirty years ago. Nevertheless, the inherent unpredictability of weather conditions persists as the most critical factor influencing crop production.

The Moscow region, for instance, experienced an average temperature that was 2.1°C above the standard deviation from 2018 to 2021. Concurrently, precipitation exhibited a decline below average in 2018 and 2021 by 20.96% and 0.9%, respectively, while in 2019, it registered as 12.2% above the mean. Such agrometeorological conditions during the growing season had a detrimental effect on crop yields and contributed to the spread of potato phytopathologies.

For instance, the 2018 growing season was characterized by unfavorable agrometeorological conditions, which generally impeded potato growth, development, and productivity, while concurrently fostering the proliferation of Alternaria. The cold weather experienced in late May and early summer 2018 led to the spread of rhizoctoniosis.

Consequently, the identification of methodologies to counteract the adverse effects of climate change and erratic weather patterns on crop yield is a pivotal concern for agricultural production. The integration of advanced technologies, including nanotechnology, holds considerable promise in this regard.

The present study corroborates the validity of the selected course of action. For instance, meteorological conditions in 2021 were conducive to the proliferation of Alternaria epiphytotica. The pre-sowing treatment of tubers with preparations No. 3, No. 4, and No. 5 provided significant protection against disease development, thereby contributing to an increase in both yield and marketable quality of potatoes. Concurrently, the efficacy of NP preparations is manifested in the inhibition of phyto diseases during the vegetation period and the reduction of the number of damaged tubers (Parsha, dry rot) of the new crop.

The effectiveness of these preparations is contingent on the composition and concentration of NPs. The most promising nanobiopreparation identified is No. 1 (NP Zn 10-2% + Cu 10-8% + Fe 10-6% + Mo 10-8%), which is introduced into the polymer coating. The film itself has been shown to protect potato tubers from infections and pests, safeguard them from wilting in drought, and prevent the diffusion of NPs into the soil. This pre-planting treatment of tubers is gaining popularity (Zhang et al., 2018). Micronutrients in the form of NPs in polymer coating have been shown to stimulate plant growth, activate biological processes, increase plant immunity, and protect potatoes from pests and diseases (Zhang et al., 2018). Iron and copper, elements with variable valence, actively participate in the Haber-Weiss reaction, resulting in the formation of highly reactive OH^{o}-radicals that damage the cell walls of phytopathogens. In addition to its fungicidal effect, copper has been shown to form stable disulfide bonds with cellular proteins, leading to pathogen cell death (Boxi, Mukherjee, & Paria, 2016; Saharan et al., 2015).

The prolonged action of the nanoparticles is attributed to their unique structural properties, which have been shown to enhance plant immunity, thereby contributing to their ability to withstand adverse weather conditions, temperature increases, and fluctuations in water availability.

5. CONCLUSION

Preparations involving micronutrient NPs in polymer coating can be recommended for the pre-planting treatment of potato tubers. This approach has been shown to reduce the prevalence and severity of damage caused by plant phytopathogens, thereby increasing potato yield and product quality in the context of climate change.

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