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The Efficacy of Plant Pathogens Control by Complexed Forms of Copper

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Abstract: Copper is a substance that has been used in plant protection for years. Currently, however, more and more attention is being paid to the need to limit the amount of it that ends up in the natural environment. At the same time, it is necessary to partially replace synthetic fungicides with alternative preparations. It is therefore worth looking for forms of copper that will contain a smaller amount of the mentioned ingredient while being highly effective. This experiment assessed the effect of selected preparations on the development of mycelium of pathogens of the *Fusarium* genus and the germination parameters of winter wheat. The efficacy of copper lignosulfonate and copper heptagluconate in seed treatment was tested, comparing them to copper oxychloride, copper hydroxide, and tebuconazole. The obtained results indicate that the use of copper lignosulfonate and copper heptagluconate allows for the effective limitation of the development of the tested pathogens (mycelium development was inhibited by up to 100%). Most of the preparations had no effect on the energy and germination capacity of winter wheat (only in one combination were the values lower than 90%). The use of preparations containing reduced doses of copper is an effective solution when applied as seed dressings.

Keywords: copper; *Fusarium*; winter wheat; seed treatment

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1. Introduction

Wheat is one of the most important crop species in the world and plays a very important role in maintaining the world's food security [1,2]. It is used to produce bread and other types of baked goods and pasta, in animal nutrition, and in industry [3]. The yield of this plant is influenced by a number of factors, including the variety, weather and soil conditions, plant nutrition, and the occurrence of weeds and pests [4–6]. A factor that can significantly reduce the volume and quality of winter wheat yield are fungal diseases [7]. An example is pathogens from the *Fusarium* genus, which can infect cereals at various stages of their development [8]. The routes through which infection occurs are diverse. The fungi may be transmitted with infected seed material air masses and can be presented in the soil [9]. They lead to a decrease in crop yields and grain contamination with mytoxins, which are harmful to human and animal health [10]. The *Fusarium* species that most commonly infect cereals are *F. culmorum*, *F. avenaceum*, *F. fujikuroi*, and *F. graminearum* [11,12].

One of the basic methods of protecting plants against pathogens is seed dressing, which aims to reduce the occurrence of seed-borne and soil-borne diseases [13,14]. Chemical seed treatments are commonly used for seed treatment [15]. One of the active substances used for this purpose is tebuconazole. It is classified as a triazole [16]. This fungicide's main effect is to inhibit 14a-demethylation of lanosterol in the pathway of ergosterol biosynthetic [17]. Ergosterol plays an important role in building the fungal cell membrane [18]. Currently, great importance is placed on reducing the amount of chemical plant protection products that are used in agriculture. This is related to a concern for human health and the natural environment [19]. It is also justified by consumer requirements regarding food quality [20]. In the European Union, it is assumed that the use of plant protection products will decrease by 50%, and that 25% of agricultural land in the European Union will be used for organic production purposes by 2030 [21]. Therefore, alternatives to chemical plant protection products are being sought [22,23].

Copper is a substance that in plant organisms influences the electron transport related to photosynthesis [24]. It is important for mitochondrial function, reduction in oxidative stress, and the lignification process [25,26]. It plays a role in the formation of regulatory proteins. It is also a cofactor of various enzymes [27]. Copper deficiency leads to stunted growth, distortion and wilting of plant leaves, and excessive tillering of cereals. It affects the level of grain yield [28,29]. Deficiencies of this microelement are reported in many parts of the world [30].

The properties of copper that are related to limiting the development of fungal pathogens have been known for centuries. Copper was a component of the Bordeaux mixture [31]. It is also used as an ingredient in bactericidal preparations [32]. Copper as a plant protection agent interferes with the activity of enzymes and affects nucleic acids, energy transport, and the permeability of pathogen cell membranes [33]. In addition to agriculture, it can also be used, among others, in the textile industry, to control infections in health care and in biomedicine [34]. Copper in plant protection can be used in various chemical compounds [35]. Commonly known forms are copper oxychloride and copper hydroxide, which have contact properties. They are sensitive to weather conditions, such as solar radiation, and easily washed away by rain [36]. Copper complexed with heptagluconic acid enhances plants' immune mechanisms. They are better taken up by plants, move within them, and are considered more environmentally friendly [37]. Currently, little data exist on the effects of copper lignosulfonate. Lignosulfonates are by-products of wood pulp. It is possible to use them as a component of fertilizers. It is characterized by slow dissolution and release. It is a good carrier of nutrients [38]. The search for new forms of copper is related to the need to limit the amount of it that enters the environment. In the European Union, plant protection products containing copper compounds should not be used at a dose exceeding 28 kg of copper per hectare over 7 years (average 4 kg $\times$ ha^{-1} per year) [39]. This applies to all plants grown during this period in a given area.

The aim of this study was to evaluate various forms of copper on the development of *Fusarium* pathogens and the germination process of winter wheat.

2. Materials and Methods

2.1. Effects of Copper on In Vitro Fungal Growth

In an in vitro experiment, the growth of mycelium after the use of various copper-containing preparations was assessed. All doses of the products are given for values applied per hectare (per 200 L of water). This research used a preparation based on copper heptagloconate (Hepta PRO; SMP Agro Sp. z o. o., Komorniki, Poland; copper content: 70 g $\times$ L^{-1}—complexed with heptagluconic acid) in a dose of 1.0 L; copper lignosulfonate (test preparation, copper content: 60 g $\times$ L^{-1}—complexed with lignosulfonate) in doses of 1.0 L, 1.2 L, 1.5 L, and 3.0 L; copper oxychloride (Miedzian 50 WP; Synthos Agro, Oświęcim, Poland; copper content: 500 g $\times$ kg^{-1} in the form of copper oxychloride) in a dose of 1 kg; and copper hydroxide (Copper Max NEW 50 WP; Spiess-Urania Chemicals GmbH, Hamburg, Germany; copper content: 500 g $\times$ kg^{-1}—in the form of copper hydroxide) in a dose of 1 kg. No plant protection product was used in the control sample. The pathogens tested in the experiment were *Fusarium avenaceum* (Fr.) Sacc., *Fusarium culmorum* (W.G.Sm.) Sacc., *Fusarium graminearum* Schwabe, and *Fusarium fujikuroi* Nirenberg. Infected plant material was collected from wheat and corn fields in 2021–2022 in Greater Poland

Voivodeship. Pieces of stems with disease symptoms were disinfected and then placed on PDA medium. Fungal colonies growing from fragments of plant material were transplanted and subjected to further incubation. Fungi were identified by assessing the morphological characteristics of colonies and macroconidia, based on available mycological keys [40,41]. Isolates are stored in the Laboratory of Mycology Department of the Institute of Plant Protection—NRI. The tested substances were added to sterile agar-glucose-potato medium (PDA) cooled to 45 °C in such quantities as to obtain the appropriate concentration of the active substance corresponding to the field. The obtained medium mixture and the agents were poured into Petri dishes. The experiment was performed in 5 repetitions. The control combination was pure PDA medium (without the addition of tested substances). Discs of individual cultures of fungal species with a diameter of 4 mm were placed on the solidified medium in Petri dishes, in their central part. The plates were incubated at 20 °C in the controlled conditions of a Binder chamber (Sanyo Electric Japan—Incubator MIR-254, PHC Europe BV, Etten-Leur, Netherlands). Incubation conditions were 20 °C for 14 h during the day/14 °C for 10 h at night, at 50% humidity. The diameter of the cultures in each combination was measured after the mycelium had overgrown the surface of the medium in a given control object or after 3 weeks for slowly growing cultures. The average growth of mycelium in millimeters was calculated. All experiments were performed in 2 independent series. The results from individual series were averaged and summarized in tables.

2.2. Rolled Towel Test

The rolled towel test (BP method) was performed in four repetitions per combination, each with 25 grains. The research material consisted of winter wheat grain (*Triticum aestivum* L.) of the variety Banatus. The grains placed on tissue paper were inoculated with a suspension of mycelium and spores of fungi of the *Fusarium* genus at a concentration of 10^6 in 1 mL. To prepare the inoculum, isolates of pathogenic fungi obtained by breeding pure cultures from plant material from wheat cultivation were used: *Fusarium avenaceum* (Fr.) Sacc., *Fusarium culmorum* (W.G.Sm.) Sacc., *Fusarium graminearum* Schwabe, and *Fusarium fujikuroi* Nirenberg. The fungal isolates used for grain inoculation came from the collection of the Department of Mycology, IOR-PIB in Poznań. For this experiment, fungal isolates were selected and multiplied on appropriate media. For pathogenicity tests, 5 isolates of the species *F. culmorum*, *F. avenaceum*, *F. fujikuori*, and *F. graminearum* were selected and multiplied. Under laboratory conditions, surface-disinfected winter wheat grains were inoculated with a spore suspension of $4 \times 10^6 \times \text{mL}^{-1}$ for all isolates. The grains were placed on filter paper in large Petri dishes, 100 pieces in 4 repetitions for each isolate. The health of the seedlings was assessed after 7 days of incubation by determining the number of coleoptiles with necrotic symptoms. The results were analyzed statistically using the variance method. One isolate from each species was selected for testing, as it caused the significantly highest percentage of infected seedlings in the test. The experiment used uninoculated and inoculated grains with *Fusarium* pathogens. The control sample was not treated with the fungi. The remaining combinations used various preparations containing copper and a synthetic fungicide. The doses were given per 100 kg of grain: copper lignosulfonate (test preparation, copper content: 60 g $\times$ L^{-1}—complexed with lignosulfonate) in doses of 0.125, 0.25, 0.5, 1.0, 1.2, 1.5, and 3.0 L; copper oxychloride (Miedzian 50 WP; Synthos Agro, Oświęcim, Poland; copper content: 500 g $\times$ kg^{-1} in the form of copper oxychloride) at a dose of 1.42 kg; copper hydroxide (Copper Max NEW 50 WP; Spiess-Urania Chemicals GmbH, Hamburg, Germany; copper content: 500 g $\times$ kg^{-1}—in the form of copper hydroxide) in a dose of 1 kg; copper heptagloconate (Hepta PRO; SMP Agro Sp. z o. o., Komorniki, Poland; copper content: 70 g $\times$ L^{-1}—complexed with heptagluconic acid) in a dose of 1.0 L; and tebuconazole (Tarcza 060 FS, Sharda Polska Sp. z o. o., Warsaw, Poland; tebuconazole—60 g $\times$ L^{-1}) in a dose of 50 mL. The grains were dressed using the HEGE 11 laboratory dressing machine for dressing small amounts of seeds with various types of dressings (WINTERSTEIGER, Bad Sassendorf, Germany). Rolls prepared using filter paper were placed in a thermostatic cabinet, where they were provided with constant humidity and a temperature of 21 °C. After 4 days from the beginning of the experiment, the germination energy of the grains was assessed (percentage of seeds normally germinated within a specific short time; high germination energy ensures good uniformity of emergence [42,43]).

$$\text{Germination energy} = (\text{number of germinated seeds: total number of seeds}) \times 100$$

After 7 days, the germination capacity of grains and the length of roots and shoots were assessed. Based on the results, the vigor index [44] was determined:

$$\text{Vigor index (VI)} = [\text{shoot length (cm)} + \text{root length (cm)}] \times \text{germination (\%)}$$

Additionally, the infection of seedlings by fungal pathogens was visually determined. The percentage of infection and infection index were assessed.

$$\text{Infection index} = \frac{(\mathrm{n(II)} \times 0.25) + \mathrm{n(III)} \times 0.75) + \mathrm{n(IV)}}{\mathrm{n(I + II + III + IV)}}$$

where:

I. no symptoms;
II. less than 50% of seedlings attacked;
III. more than 50% of seedlings attacked;
IV. 100% of seedlings attacked.

2.3. Statistical Analysis

Results were analyzed with Statistica 13 software (StatSoft Ltd., Kraków, Poland). Analysis of variance (ANOVA) to determine significant differences between treatments was used. Means were separated by protected Tukey's HSD test at p = 0.05 to isolate homogeneous groups, when the F-test indicated significant factorial effects. Results were obtained in single, representative experiments.

3. Results

All preparations containing copper contributed to a statistically significant reduction in the growth of mycelium of pathogens of the *Fusarium genus* (Table 1). In the case of *F. culmorum*, the use of copper heptagluconate, lignosulfonate at a dose of 1.5 L × ha^{-1} and 3 L × ha^{-1} and copper oxychloride contributed to the complete inhibition of mycelium development. For *F. graminearum*, all the preparations that were used contributed to a statistically equal reduction in the development of the fungus. Copper heptagluconate, copper lignosulfonate in the three higher doses, and copper hydroxide contributed to the best effect in limiting the development of *F. fujikuori* mycelium. The results obtained during the study of *F. avenaceum* indicate that copper lignosulfonate used at a dose of 1 L × ha^{-1} significantly limited the development of the mycelium of the mentioned pathogen, while other solutions led to the complete inhibition of this process.

The results obtained in the experiment indicate that most of the preparations used in the experiment did not have a statistically significant effect on the energy and germination capacity of winter wheat grains (Table 2). In the case of the energy and germination capacity of uninoculated grain, copper lignosulfonate used at a dose of 3.0 L × 100 kg^{-1} of grain contributed to a statistically significant reduction in the values of these parameters; however, they remained at the levels of 75.0% and 89.0%. For tests in which grain inoculated with pathogens of the *Fusarium* genus were used, the use of copper lignosulfonate at a dose of 3 L × 100 kg^{-1} of grain contributed to a statistically significant decrease in the germination energy level to 82.0%, but it had no effect on the germination capacity, where no statistically significant differences between individual combinations were found.

Table 1. The effect of copper-containing preparations on the growth of mycelium of pathogens of the *Fusarium* genus.

No.	Preparation	Dose per 200 L of Water	Surface of the Mycelium (mm)			
			Fusarium culmorum	*Fusarium graminearum*	*Fusarium fujikuori*	*Fusarium avenaceum*
1	Control	-	90.0 a	90.0 a	90.0 a	90.0 a
2	Copper heptagluconate	1.0 L	0.0 d	0.0 b	1.7 d	0.0 c
3	Copper lignosulfonate	1.0 L	14.3 b	0.0 b	18.0 b	7.7 b
4	Copper lignosulfonate	1.2 L	8.0 c	0.0 b	1.7 d	0.0 c
5	Copper lignosulfonate	1.5 L	0.0 d	0.0 b	1.7 d	0.0 c
6	Copper lignosulfonate	3.0 L	0.0 d	0.0 b	1.7 d	0.0 c
7	Copper oxychloride	1.0 kg	0.0 d	0.0 b	12.7 c	0.0 c
8	Copper hydroxide	1.0 kg	8.3 c	1.7 b	0.0 d	0.0 c
	HSD (0.05)		2.5	1.8	4.1	1.0

Different letters a–d indicate statistically different mean values (α = 0.05).

Table 2. The effect of preparations containing copper and synthetic fungicide on the energy and germination capacity of winter wheat grain.

No.	Preparation	Dose per 100 kg of Grain	Grain Not Inoculated with *Fusarium*		Grain Inoculated with *Fusarium*	
			Germination Energy (%)	Germination Capacity (%)	Germination Energy (%)	Germination Capacity (%)
1.	Control	-	99.0 a	100.0 a	94.0 a	95.0 a
2.	Copper lignosulfonate	0.125 L	99.0 a	99.0 a	94.0 a	98.0 a
3.	Copper lignosulfonate	0.25 L	96.0 a	100.0 a	97.0 a	98.0 a
4.	Copper lignosulfonate	0.5 L	97.0 a	98.0 a	94.0 a	95.0 a
5.	Copper lignosulfonate	1.0 L	97.0 a	99.0 a	92.0 a	97.0 a
6.	Copper lignosulfonate	1.2 L	96.0 a	99.0 a	92.0 a	96.0 a
7.	Copper lignosulfonate	1.5 L	93.0 a	99.0 a	97.0 a	98.0 a
8.	Copper lignosulfonate	3.0 L	75.0 b	89.0 b	82.0 b	95.0 a
9.	Copper oxychloride	1.42 kg	91.0 a	96.0 a	94.0 a	95.0 a
10.	Copper hydroxide	1.0 kg	97.0 a	99.0 a	97.0 a	99.0 a
11.	Copper heptagluconate	1.0 L	90.0 a	100.0 a	93.0 a	98.0 a
12.	Tebuconazole	50 mL	98.0 a	98.0 a	97.0 a	100.0 a
	HSD (0.05)		5.5	3.8	6.2	5.4

Different letters a,b indicate statistically different mean values (α = 0.05).

The used preparations had a different level of effect on the length of shoots, depending on whether the treated grain was uninoculated or inoculated (Figure 1). In the case of uninoculated grain, only the result obtained in the combination in which copper lignosulfonate was used at a dose of 3 L × 100 kg^{-1} grain was found to be statistically significantly lower than the others. The highest values of shoot lengths for seedlings grown from inoculated grains were observed for the combinations in which copper lignosulfonate was used at doses of 0.125 L and 0.25 L per 100 kg of grain. The most significant reduction in the length of shoots, again, as in the case of healthy seedlings, was recorded for the application of copper lignosulfonate at a dose of 3 L × 100 kg^{-1} of grain.

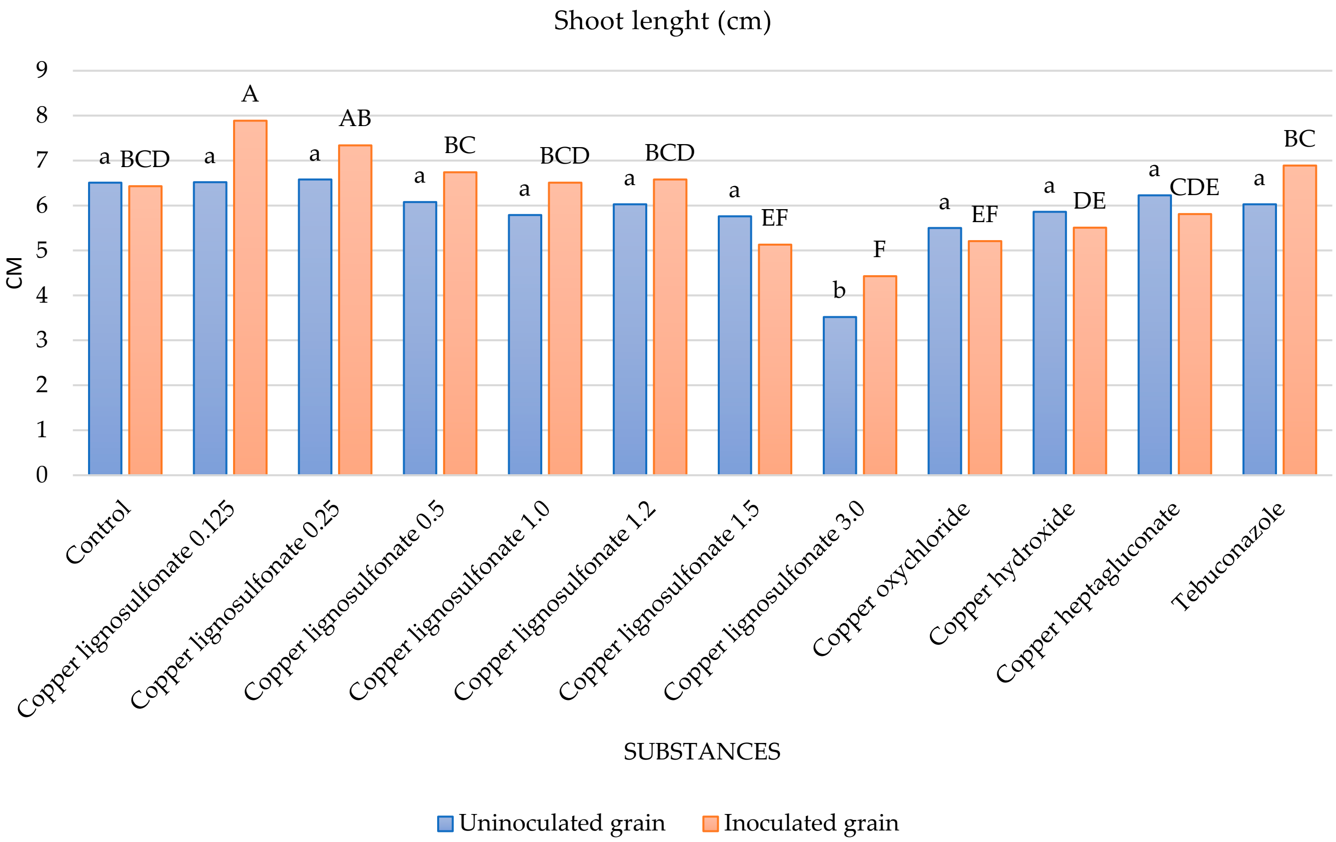

Figure 1. The effect of preparations containing copper and a synthetic fungicide on the length of winter wheat shoots. 1—control, 2–8—copper lignosulfonate (different doses per 100 kg of grain: 2—0.125 L, 3—0.25 L, 4—0.5 L, 5—1.0 L, 6—1.2 L, 7—1.5 L, 8—3.0 L), 9—copper oxychloride, 10—copper hydroxide, 11—copper heptagluconate, 12—tebuconazole. The doses of preparations of combinations 1–12 are consistent with the numbers and values given in Table 2. Different letters indicate statistically different mean HSD (0.05): uninoculated grain = 0.801 (lower-case letters); inoculated grain = 0.765 (capital letters). Standard deviation: uninoculated grain = 0.557; inoculated grain = 0.532.

The experiment showed a statistically significant effect of selected preparations on the root length of winter wheat seedlings (Figure 2). The lowest value of this parameter, both for seedlings grown from inoculated and uninoculated grains, was found for the combinations in which the grain was treated with copper lignosulfonate at a dose of 3 L × 100 kg^{-1} grain, copper oxychloride, and copper hydroxide. The lowest doses of copper lignosulfunate contributed to an increase in root length.

In the case of seedlings grown from uninoculated grain, the seedlings showed the greatest vigor in the case of grain dressing with the two lowest doses of copper lignosulfonate. For inoculated grain, the highest values of the mentioned parameter were found for the control, and in combinations in which the four lowest doses of copper lignosulfonate and tebuconazole were used (Figure 3). In both variants, the use of too high a dose of copper lignosulfonate contributed to a significant decrease in the level of vigor.

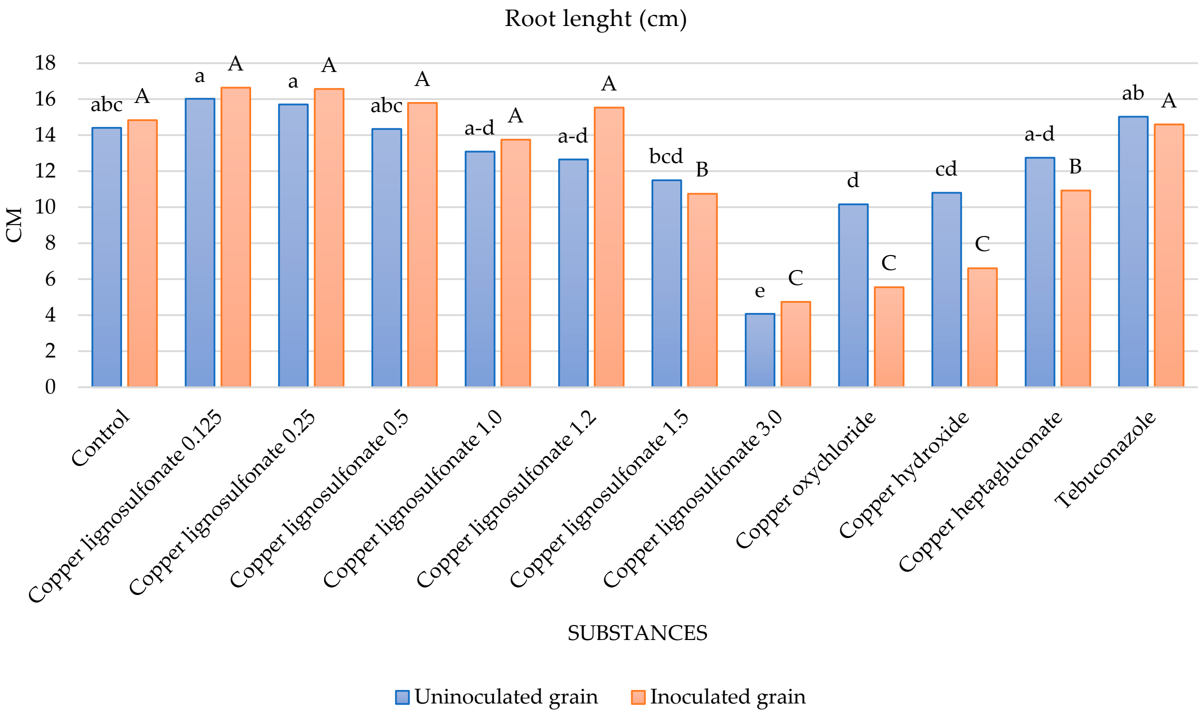

Figure 2. The effect of preparations containing copper and a synthetic fungicide on the length of winter wheat roots. 1—control, 2–8—copper lignosulfonate (different doses per 100 kg of grain: 2—0.125 L, 3—0.25 L, 4—0.5 L, 5—1.0 L, 6—1.2 L, 7—1.5 L, 8—3.0 L), 9—copper oxychloride, 10—copper hydroxide, 11—copper heptagluconate, 12—tebuconazole. The doses of preparations of combinations 1–12 are consistent with the numbers and values given in Table 2. Different letters indicate statistically different mean HSD (0.05): uninoculated grain = 2.614 (lower-case letters); inoculated grain = 2.016 (capital letters). Standard deviation: uninoculated grain = 1.817; inoculated grain = 1.401.

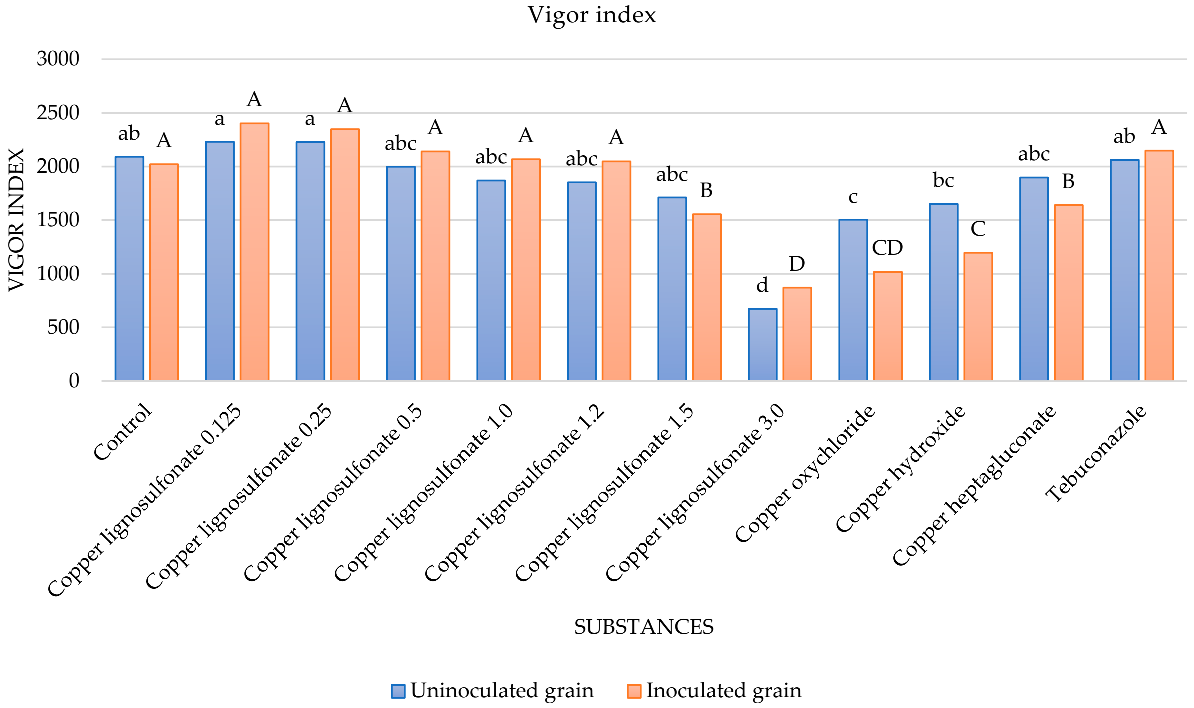

Figure 3. The effect of preparations containing copper and a synthetic fungicide on the vigor index. 1—control, 2–8—copper lignosulfonate (different doses per 100 kg of grain: 2—0.125 L, 3—0.25 L, 4—0.5 L,

5—1.0 L, 6—1.2 L, 7—1.5 L, 8—3.0 L), 9—copper oxychloride, 10—copper hydroxide, 11—copper heptagluconate, 12—tebuconazole. The doses of preparations of combinations 1–12 are consistent with the numbers and values given in Table 2. Different letters indicate statistically different mean HSD (0.05): uninoculated grain = 331.4 (lower-case letters); inoculated grain = 258.3 (capital letters). Standard deviation: uninoculated grain = 230.389; inoculated grain = 179.538.

All preparations that were used contributed to a decrease in the infection index value. The highest level of this parameter was recorded for copper lignosulfonate at doses of 0.125 L and 0.25 L per 100 kg of grain (Figure 4).

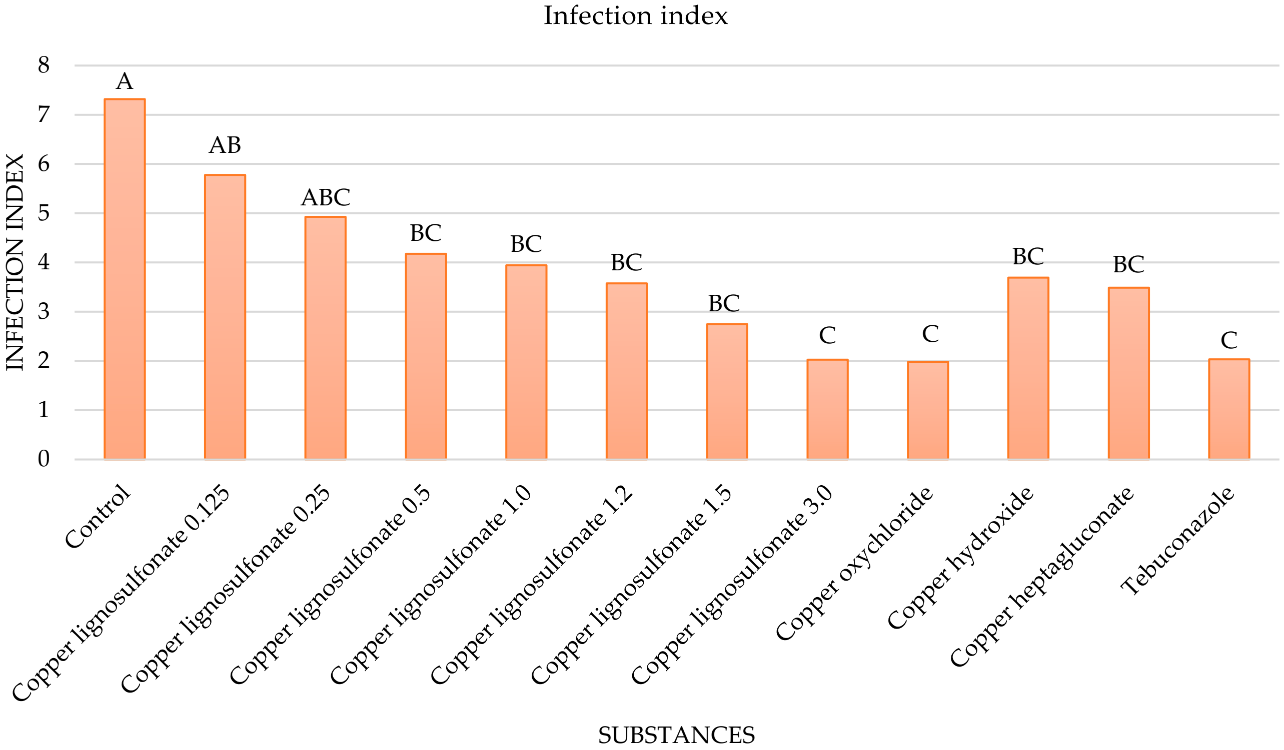

Figure 4. The influence of preparations containing copper and a synthetic fungicide on the infection index. 1—control, 2–8—copper lignosulfonate (different doses per 100 kg of grain: 2—0.125 L, 3—0.25 L, 4—0.5 L, 5—1.0 L, 6—1.2 L, 7—1.5 L, 8—3.0 L), 9—copper oxychloride, 10—copper hydroxide, 11—copper heptagluconate, 12—tebuconazole. The doses of combination preparations 1–12 are consistent with the numbering and values given in Table 2. Different letters indicate statistically different mean HSD (0.05) = 2.1878. Standard deviation = 1.521.

The preparations containing copper and tebuconazole contributed to a decrease in the percentage of infection compared to the control. An increase in the dose of copper lignosulfonate led to increasingly lower values of this parameter. Copper heptagluconate, copper hydroxide, copper oxychloride, and tebuconazole also contributed to a statistically significant decrease in the value of this parameter (Figure 5).

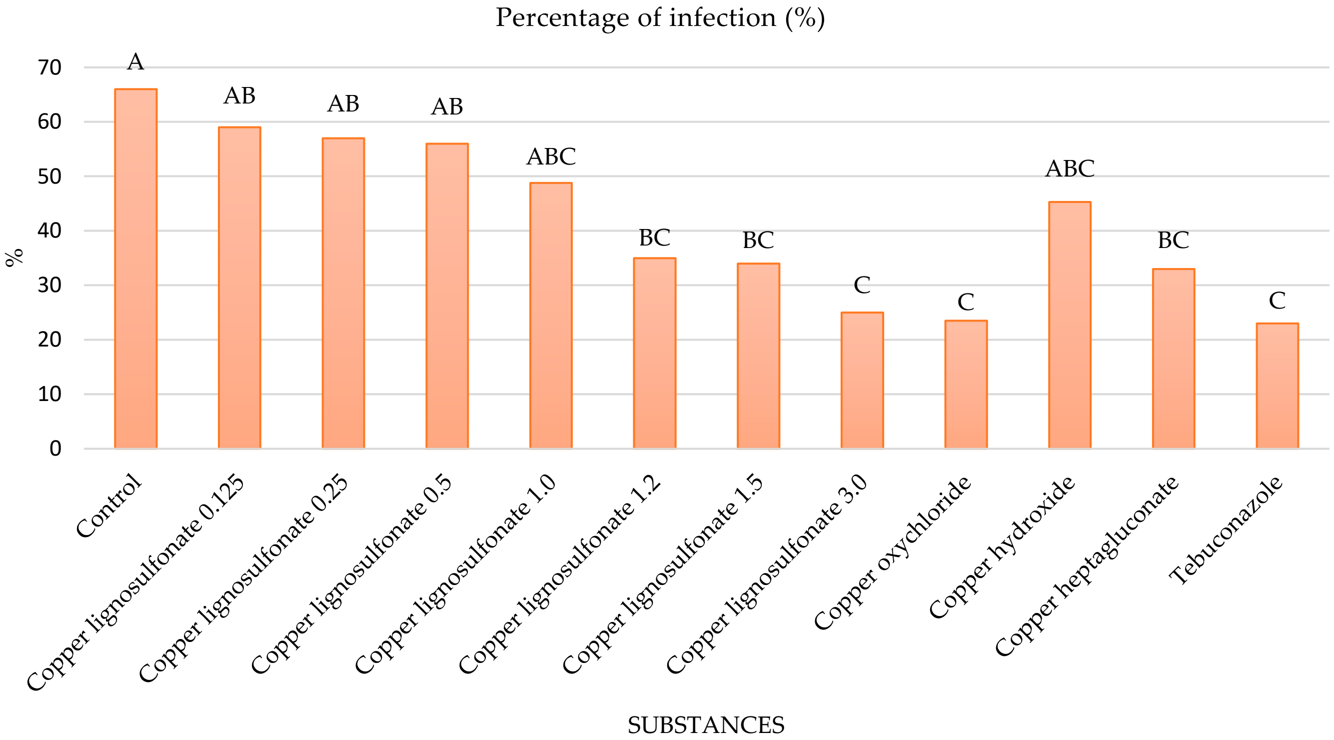

Figure 5. The influence of preparations containing copper and a synthetic fungicide on the percentage of infection. 1—control, 2–8—copper lignosulfonate (different doses per 100 kg of grain: 2—0.125 L, 3—0.25 L, 4—0.5 L, 5—1.0 L, 6—1.2 L, 7—1.5 L, 8—3.0 L), 9—copper oxychloride, 10—copper hydroxide, 11—copper heptagluconate, 12—tebuconazole. The doses of combination preparations 1–12 are consistent with the numbering and values given in Table 2. Different letters indicate statistically different mean HSD (0.05) = 19.45. Standard deviation = 13.52.

4. Discussion

Pathogens of the *Fusarium* genus may contribute to a significant decrease in the yield of winter wheat. They also lead to the contamination of agricultural produce with mycotoxins [45]. Seed dressing helps reduce the risk of disease infection from the beginning of crop development. Synthetic fungicides are often used for this purpose, but it is necessary to limit their use [46]. In this experiment, the use of copper compounds allowed us to limit the development of *Fusarium* pathogens at a level that is similar to that of a triazole fungicide.

In the experiment, too high a dose of a preparation containing copper lignosulfonate i (a form that is conducive to its high effectiveness) contributed to limited grain germination and development of winter wheat seedlings. This concerned both healthy seeds and those infected with *Fusarium* pathogens. This microelement is necessary for the proper functioning of plants. However, in too large doses, it is toxic to them. It may contribute, among other things, to limiting seed germination [47]. Singh et al. [48] confirmed this fact for winter wheat in their research. They also showed the unfavorable effect of too high a dose of copper on various parameters (including the content of chlorophyll and carotenoids) in relation to seedlings of the mentioned crop plant. Hafeez et al. [49] showed a tendency that is similar to the results obtained in this experiment—the appropriate dose of the tested form of copper did not affect the germination capacity of winter wheat grains in the cited work; rather, only too large an amount of the discussed ingredient had an adverse effect on the germination process.

Excessive amounts of copper contributed to limiting the development of roots to a greater extent than in the case of shoots. This may be related to a greater tendency to accumulate the discussed microelement in the roots [50]. In research conducted by Dias et al. [51], a greater accumulation of copper was observed in the roots than in the shoots. Various levels of copper accumulation in the roots were also found, depending on the form of copper. The results obtained during the conducted research indicate that copper lignosulfonate and copper heptagluconate had a smaller impact on the development of wheat roots and shoots than copper oxychloride and copper hydroxide did. In the case of copper lignosulfonate, only too high a dose significantly reduced the value of the discussed parameter, while the lowest dose had a stimulating effect on the roots of seedlings grown from the inoculated grain.

All the used copper compounds contributed to limiting the development of *Fusarium* pathogens. The degree of this depended on the form of the substance in question. In research conducted by Bhimani et al. [52], the authors found a significant impact of copper oxychloride and copper hydroxide on the development of a pathogen of the *Fusarium* genus. One of the newer solutions used in the experiment is copper heptagluconate. In the experiment conducted by González-Hernández et al. [53], copper heptagluconate was used for soil drainage, and then, disease symptoms caused by bacteria on the leaves were assessed. The application of the mentioned compound contributed to a reduction in plant infection, which proves the high mobility of copper heptagluconate. This may allow for the effective activity of this compound being used to treat grain. Copper can help reduce the development of fungal diseases in various ways. The previously mentioned article stated that the use of copper heptagluconate contributed, among other things, to increasing the production of polyphenols in plants. These substances support the immune processes of plants against fungal pathogens [54]. Copper contributes to the denaturation of proteins and enzymes of these organisms. Additionally, it inhibits the formation of acetyl-CoA and ATP [55]. Currently, more and more attention is paid to the need to reduce the amount of copper that ends up in the soil. This substance contributes to threats to the development of plants and microorganisms and the safety of the natural environment. Therefore, more attention should be paid to the use of products with a reduced amount of this microelement [56,57]. In the conducted research, individual copper compounds contributed to the reduction in *Fusarium* pathogens. It is worth noting that the copper content differed between the preparations, but the effectiveness of the products containing copper lignosulfonate and copper heptagluconate, characterized by a reduced copper content, was at a similar level to traditional forms with a high copper content and synthetic fungicides.

Copper lignosulfonate is a new solution used for dressing grain. The experiment examined how high a dose of the substance in question would effectively limit the development of *Fusarium* pathogens and at the same time be safe for winter wheat seedlings. The results indicate that the use of 1 L of copper lignosulfonate to treat 100 kg of winter wheat grain allows us to achieve these goals. It is also indicated that lignosulfonates are a good carrier of fertilizers and have a biostimulating effect on plants [58], so they may have a beneficial effect on plant development. Lignin contained in these compounds has a positive effect, among others, on the photosynthesis, respiration, and hormonal balance of plants [59]. A beneficial effect on seedling development was observed, especially when the lowest dose of copper lignosulfonate was used.

5. Conclusions

Research on new solutions for plant protection is important due to environmental aspects, the withdrawal of various active substances, and the problem of pathogen resistance. Biological preparations have been gaining in importance in recent years, but currently, there is a lack of them that could be used to control certain diseases, and these products are very dependent on the prevailing meteorological conditions. In many cases, copper can be an effective solution. The obtained results indicate that preparations containing new forms of copper with a lower content of the discussed ingredients—copper lignosulfonate and copper heptagluconate—have an effectiveness level that is similar to those of copper hydroxide, copper oxychloride, and tebuconazole. However, complex forms of copper have a significantly reduced content of the substance in question, so they are safer for the environment. The dosage of individual preparations should be adjusted not only to the effectiveness of pathogen control, but also to the effect on the treated plants. Copper is an important ingredient for the proper functioning of plants, but too much of it may negatively affect them. Individual forms of copper have different levels of uptake by plants, so the dose should be adjusted for a specific preparation.

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