



Article

Fungicidal and Stimulating Effects of Heteroleptic Copper Complex on the Germination and Phytosafety of Plants

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Abstract: At present, when the whole world is intensively switching to organic farming, the refusal or minimization of the usage of chemical plant protection products and synthesized fertilizers is a very urgent issue for the agro-industrial complex (AIC). Accordingly, the solution to the problems of increasing yields and ensuring the fight against pathogenic components should be carried out in accordance with the principles of “green” chemistry. In this regard, the usage of heteroleptic complexes based on carboxylic and amino acids with biogenic metals is dictated not only by their availability, low cost, and ability to increase crop yields but also by fungicidal activity, lower toxicity, and easy biodegradability, which lists them among the “green” and cost-effective plant biostimulants. In the present work, for the first time, a heteroleptic complex based on succinic acid and glycine, with the formula $[\text{Cu}(\text{succ})(\text{gly})]$, was developed for usage as a fungicidal biostimulant, which has the ability to significantly reduce the number of pathogens. We found that this compound has a layered structure and was able to increase soybean germination up to 100%.

Keywords: succinic acid; glycine; copper; complex; fungicidal; stimulating effect



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1. Introduction

In the last decade, the study of copper complexes containing different ligands has played an important role in the field of agricultural chemistry. In plants, copper is involved in the synthesis of iron-containing enzymes and activates plant respiration, photosynthesis, carbohydrate metabolism, and the formation of vitamins P and B [1,2]. Being a vital element, copper actively reacts with amino acids [3,4], carboxylic acids, and nitrogenous bases [5–7], forming highly stable complexes.

In reference [8], researchers successfully synthesized new copper-based complexes aimed at plant protection, which possess both antimicrobial and fungicidal properties. Moving on to reference [9], investigators discovered that the complex formed by salicylaldehyde and phenylenediamine with copper demonstrated remarkable efficacy against various strains of bacteria, including *E. coli* spp., *Staph* spp., and *Aniger C. albicans*. Lastly, the authors [10] concluded that two mononuclear pentacoordinate copper (II) complexes displayed excellent antioxidant properties against plant pests. Furthermore, organic acids have emerged as essential components in modern agricultural practices, exerting a significant influence on plant life by acting as growth-stimulating agents and providing essential substances required for biological processes. These organic acids indirectly contribute

to the regulation of plant growth and development, fostering the production of crucial metabolic regulators. Notably, amino acids play a vital role in regulating plant resilience against stress factors [11,12]. Amino acids and their derivatives demonstrate insecticidal, fungicidal, and herbicidal properties at specific concentrations [13–16]. Extensive research has shown that numerous amino acids effectively impede the activity of various target enzymes within the biochemical metabolic pathways of weeds, fungi, and insects, thereby disrupting their vital functions [13]. As a result, methods utilizing amino acids have gained substantial commercial traction, finding application as biostimulants and plant protection products, ensuring their growing prominence in the field.

Combining amino acids with microelements in organo-mineral fertilizers results in several beneficial effects on plant growth. These fertilizers stimulate germination, seed germination, and vegetative growth, while also exerting a robust anti-stress effect and serving as potent activators of metabolic processes in plants. Additionally, the presence of chelating agents plays a crucial role in enhancing the overall efficacy of these fertilizers by significantly increasing the digestibility and absorption of microelements by plants.

Presently, copper compounds are experiencing growing adoption in fighting the proliferation of bacterial pathogens causing plant diseases. Nonetheless, the adverse environmental effects and the development of bactericide resistance among bacteria pose challenges to copper's continued use in agricultural practices [17]. Consequently, there is a pressing need for the advancement of contemporary methods and tools to safeguard crops from bacterioses. These solutions should be highly effective, resource-efficient, eco-friendly, and possess a broad spectrum of actions to meet the practical demands of modern agriculture.

The relevance of studying the complexation of different ligands with biogenic elements is due to their amphoteric properties, their ability to participate in redox and complexation reactions, as well as their electrophilic and nucleophilic properties. The main advantage of metal complexes is their increased uptake by plants to improve germination and growth due to their biologically active form and high membrane permeability. Another important characteristic of metal complexes is their ability to convert toxic particles into low-toxic or even biologically active ones by binding them into stable complexes in water or soil.

The massive usage of nitrogen- and phosphorus-containing fertilizers, as well as chemical plant protection products, has led to the accumulation of various substances in biocenosis objects, putting a burden on natural ecosystems [18,19]. Recent studies have shown that not only mineral fertilizers and chemical plant protection products but also complexones accumulating in the world's oceans cause the dissolution of deposits of toxic metals with their transition into lipid-soluble complexes, which lead to the poisoning of flora and fauna [20,21]. In this regard, metal complexes based on succinic acid and their derivatives are less toxic and easily biodegradable in natural conditions, while being able to increase crop yields and improve product quality [22,23]. In addition, the usage of metal complexes provides a source of trace elements for plants in agriculture to improve germination and growth due to the biologically active form of the trace elements and high membrane permeability [24].

Another equally important property of succinic acid and its derivatives is their bactericidal and fungicidal activity, which allows the use of their metal complexes as ecological biological products in order to reduce the usage of fungicides and pesticides [25–27]. It has been established that succinic acid plays the role of signaling compounds that are integrated into the energy and hormonal systems of plants and regulate energy metabolism in plants, easily penetrating seeds and tissues during their processing [28]. At the same time, succinic acid is effective in low concentrations.

Being a precursor of chlorophyll (glycine affects the efficiency of photosynthesis and also is a protein component), glycine has the ability to integrate into the plant skeleton along with trace elements, in our case—copper, which means the plant takes in a nutrient while sending a chelator to the soil. In addition, glycine, as a component of structural proteins, strengthens cell walls and limits the penetration of pathogens into plant tissues.

This work is devoted to the synthesis of a copper complex supported by eco-bioligands, in particular, succinic acid and glycine for the treatment of leguminous crops, in order to identify biological efficiency against soybean pathogens.

2. Experimental Section

2.1. Materials

Succinic acid ($\geq 99.0\%$), copper(II) nitrate trihydrate (99.99%), glycine ($\geq 99.0\%$), and sodium hydroxide were purchased from Sigma-Aldrich. Absolute ethyl alcohol (99.7–99.8 vol%) was purchased from PubChem. All the reagents were used without additional purification.

2.2. Synthesis of $[\text{Cu}(\text{succ})(\text{gly})]_n$

A solution of sodium succinate, synthesized according to a previously published procedure [6], was added dropwise to an alcoholic solution of copper nitrate prepared by dissolving 0.242 g 1 mmol of $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ in 40 cm^3 of ethanol (1:1 ratio). The blue solution was stirred for 30 min at 50°C , after which it was cooled to 25°C . After cooling, an alcohol solution of 1 mmol of glycine was added to the solution with continuous stirring. The dark blue solution was stirred for 30 min. The solution was then treated in an ultrasonic bath, U-sonic UZTA-0.15/22-0 (Biysk, Russia), at a frequency of 30–35 kHz for 30 min. The solution was left for 24 h to crystallize, resulting in long blue needle crystals, which were isolated by filtration (Figure 1). The yield of the obtained heteroleptic complex was equal to 35%.

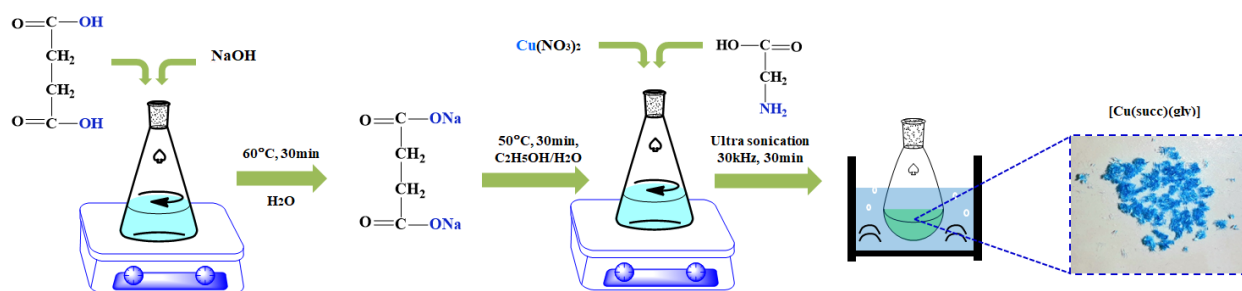


Figure 1. Scheme for obtaining a heteroleptic complex of copper with succinic acid and glycine $[\text{Cu}(\text{succ})(\text{gly})]$.

2.3. FTIR Spectroscopy

An FTIR analysis was performed on a spectrometer, the FTIR FT-801 (Simex, Russia), at a resolution of 1 cm^{-1} in the range of $500\text{--}4000 \text{ cm}^{-1}$, according to the standard procedure, producing a tablet containing potassium bromide in a ratio of 1/10 substances, at room temperature and with 100 scans. Before use, the potassium bromide was crushed and calcined at 200°C for 3 h.

2.4. UV Analysis

The UV spectra were recorded on a spectrophotometer (PE-5400UV, Moscow, Russia) at a scanning speed of 240 nm/min and a wavelength of $190\text{--}1000 \text{ nm}$. The 10 mm thick quartz cuvette was used.

2.5. Powder X-ray Diffraction Studies

The crystal structures of the substances were studied by powder X-ray diffraction on an X 'PertPRO diffractometer (Malvern Panalytical Empyrean, Amsterdam, The Netherlands) using monochromatized copper ($\text{CuK}\alpha$) radiation with a scan step of 0.02° , K-Alpha1 [$\text{\AA}$] 0.1542. The measurement angle was $10\text{--}45^\circ$, the X-ray tube voltage was 45 kV, the current intensity was 30 mA, the measurement time at each step was 0.5 s, and an aluminum rectangular multi-purpose sample holder (PW1172/01) was used for the measurement in

reflection mode. The ICDD PDF-4/AXIOM database of XRD patterns was used for the analysis of the XRD patterns.

2.6. NMR Analysis

The ^1H (500.15 MHz) and ^{13}C (125.77 MHz) nuclear magnetic resonance spectra were acquired in a D_2O solution using a JNM-ECA-500 (Jeol, Tokyo, Japan) spectrometer with tetra-methylsilane (TMS) as an internal standard for ^1H -NMR analysis. The D_2O signals were suppressed by pulse sequence (wgh_dpfge-1-1).

2.7. SEM Analysis

The surface morphologies of the complex were examined using a Quanta 200i 3D SEM (FEI, Amsterdam, The Netherlands). The measurements were carried out in high vacuum mode using a secondary electron detector at an accelerating voltage of 5 kV.

2.8. Determination of the Effectiveness of $[\text{Cu}(\text{succ})(\text{gly})]$ in the Laboratory

A mycological analysis was carried out to study the effect of the complex on germination and the degree of infection of seeds of the soybean variety «Nur+». The germination, viability, and infection of the soybean seeds under laboratory conditions were determined according to a previously described procedure [29–31]. In order to do this, the seed material was laid out on a laboratory table and distributed in an even layer. Two diagonal lines were drawn across the seeds, and the required amount was taken from the total mass of the distributed seeds. Before analysis, it was necessary to prepare strips of filter paper sized 50×20 cm. Using tweezers, the seeds were laid out with the germ part down on double strips of filter paper moistened with distilled water, covered with another layer of filter paper and polyethylene film, then rolled up into a tight roll. The rolls were placed in a vessel with water and the vessels were placed on shelves with fluorescent lamps at an illumination mode of 3000–4000 lx and 16 h of natural light, at a temperature of $+20 \pm 5$ °C. The viewing and recording of data was carried out on the 12–14th days. During the analysis, the roll was laid out on a clean table, and the top sheet of filter paper was removed. Each young shoot was examined with a monocular microscope (Micros OVE-MG 8751/1, Austria). The presence and type of pathogen were taken into account. For more accurate species identification, the pathogens were transplanted onto Czapek's nutrient medium.

3. Results and Discussion

3.1. FTIR Analysis

Figure 2 shows the FTIR spectra of glycine, succinic acid, and the $[\text{Cu}(\text{succ})(\text{gly})]$ complex. The spectrum of glycine shows stretching vibration of the HCH and NH groups in the regions of 2167 cm^{-1} to 2598 cm^{-1} and from 2794 cm^{-1} to 3441 cm^{-1} (Figure 3(a)). The band at 1498 cm^{-1} characterizes the symmetric stretching vibration of the COO^- group; the band at 1323 cm^{-1} characterizes the stretching vibration of the $-\text{CH}_2$ group; the deformation vibration C–H has an absorption band in the region of 929 cm^{-1} ; the bands in the region of 1043 cm^{-1} and 889 cm^{-1} characterize the different stretching vibrations of the C–N and C–C bonds [32,33]. In the IR spectrum of succinic acid, the O–H in the carboxyl group is characterized by an absorption band at 3200 cm^{-1} and the C–H at 2942 cm^{-1} ; the absorption bands in the regions of 1725 cm^{-1} and $1570\text{--}1550\text{ cm}^{-1}$ cause antisymmetric and symmetric stretching vibrations of the C=O carbonyl group (Figure 3(b)) [34]. The IR spectrum of the synthesized $[\text{Cu}(\text{succ})(\text{gly})]$ complex is shown in Figure 3(c). The shift of the signals of the carboxyl group in the molecules of glycine and succinic acid in the region of 1523 cm^{-1} indicates the successful formation of the $[\text{Cu}(\text{succ})(\text{gly})]$ complex. The data obtained are in good agreement with the previously obtained results [35].

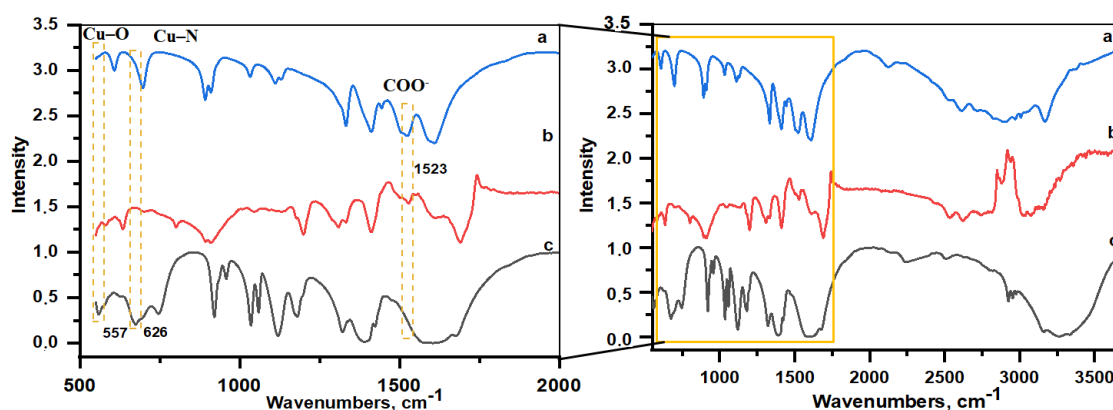


Figure 2. FTIR spectrum: a—Glycine; b—Succinic acid; c—Complex[Cu(succ)(gly)].

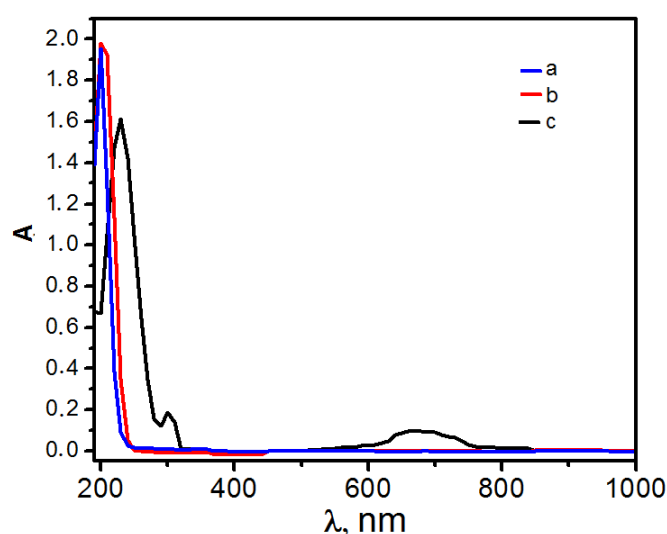


Figure 3. UV absorption spectrum: a—Glycine; b—Succinic acid; c—Complex[Cu(succ)(gly)]_n.

The appearance of a new band at 557 and 626 cm^{-1} characterizes the absorption band of the copper–succinic acid Cu–O bond fragment and the Cu–N bonds with nitrogen in the glycine molecule [6,36]. And, at 3200 cm^{-1} , a large absorption signal characteristic of the NH group in the glycine molecule can be seen. This indicates the presence of two ligands in the coordination sphere. The absence of the $\nu(\text{O-H})$ absorption band in the [Cu(succ)(gly)] complex (Figure 3(c)) indicates the loss of a proton for the OH group in the succinic acid, and the coordination of amino acids establishes that these acids are negative bidentate ligands, which are coordinated by the carboxyl group [37–39].

3.2. UV Analysis

Comparative UV absorption studies of an aqueous solution of glycine, succinic acid, and the complex of [Cu(succ)(gly)] are shown in Figure 3. In Figure 3(a and b), it can be seen that glycine and succinic acid have only one absorption band, while the spectrum of the [Cu(succ)(gly)] complex (Figure 3(c)) has three absorption bands that are shifted towards higher frequencies. Three absorption signals at wavelengths of 230 nm , 302 nm , and 678 nm were recorded for the complex [Cu(succ)(gly)] (Figure 3(c)). The absorption band shifts $\pi\text{-}\pi$ and $n\text{-}\pi$ at 230 and 302 nm indicate the coordination of ligands to metal ions [38–40]. An intense band at 230 nm is due to interligand $\pi\text{-}\pi^*$ transitions [6], and absorption at 302 nm is typical for $n\text{-}\pi^*$ or load transfer ligand metal (LTLM), which indicates the formation of Cu–O between the carboxyl group and the copper ion [41]. The absorption band at 678 nm indicates the d-d transition of electrons in copper ions [42]. A similar result was obtained in [43].

3.3. XRD Analysis

According to the diffraction pattern, the monoclinic space group $P 1 21/c 1$ of the initial glycine is shown in Figure 4a and corresponds to γ -glycine. Succinic acid has a monoclinic crystal structure and the space group $P 1 21/c 1$ (Figure 4b). It was also found that the crystal structure of glycine and succinic acid correspond to the ICDD PDF-4/AXIOM database.

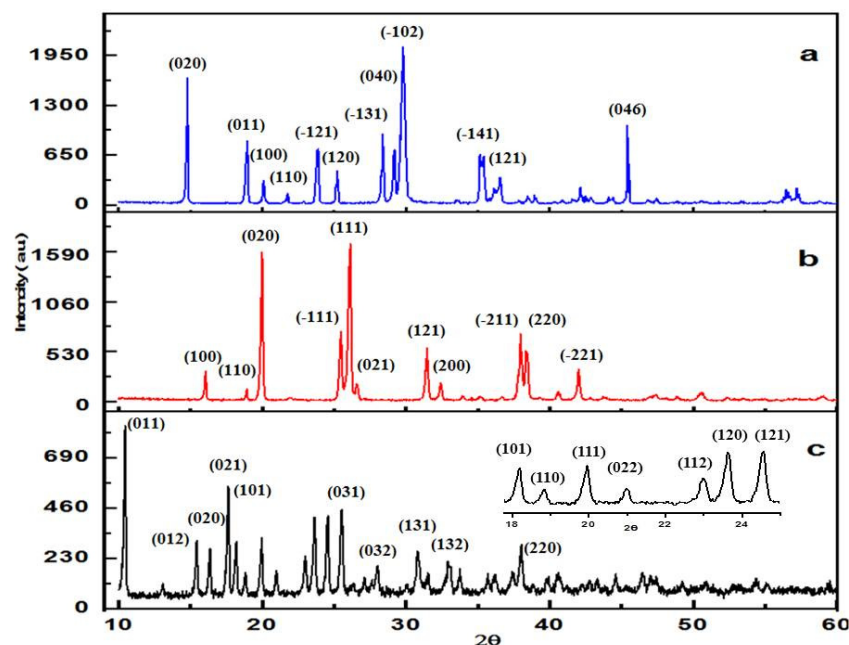


Figure 4. XRD patterns: (a)—Glycine; (b)—Succinic acid; (c)—Complex [Cu(succ)(gly)].

Figure 4c shows the XRD diffractogram of the [Cu(succ)(gly)] complex. Based on the obtained data, it can be assumed that the [Cu(succ)(gly)] complex has a crystalline structure and belongs to the orthorhombic space group [34,40]. Previous studies have already established the optimal synthesis parameters for the production of Cu succinate. The crystal structure of the obtained complex is similar to the structure [Cu(succ)(gly)] [44].

3.4. NMR Analysis

An NMR analysis was carried out to clarify the connection of succinic acid and glycine with copper ions in comparison with the FTIR spectrum. In the ^1H NMR spectrum, the signal at $\delta = 3.51$ ppm corresponds to the $(-\text{CH}_2-)$ aliphatic group in the glycine molecule; $\delta = 2.49$ ppm characterizes the $(-\text{CH}_2)_2$ aliphatic group in succinic acid; $\delta = 0.97$ ppm determines the resonant absorption of the proton in NH associated with Cu^{2+} (Figure 5). The resonance of the carboxylic protons $(-\text{COOH})$ was not detected in the spectra of the three complexes.

In accordance with the ^{13}C NMR spectra, the resonances at $\delta = 176.51$ and $\delta = 166.72$ ppm characterize the quaternary carbon atoms of carboxyl groups; $\delta = 29.80$ and $\delta = 23.72$ ppm correspond to methylene groups $(-\text{CH}_2)_2$ and $-\text{CH}_2$ in the molecules of the succinic acid and glycine (Figure 6). This shows that the succinic acid and glycine were connected in the form of a Cu^{2+} multiligand. The obtained result was consistent with the result of the FTIR in Figure 2.

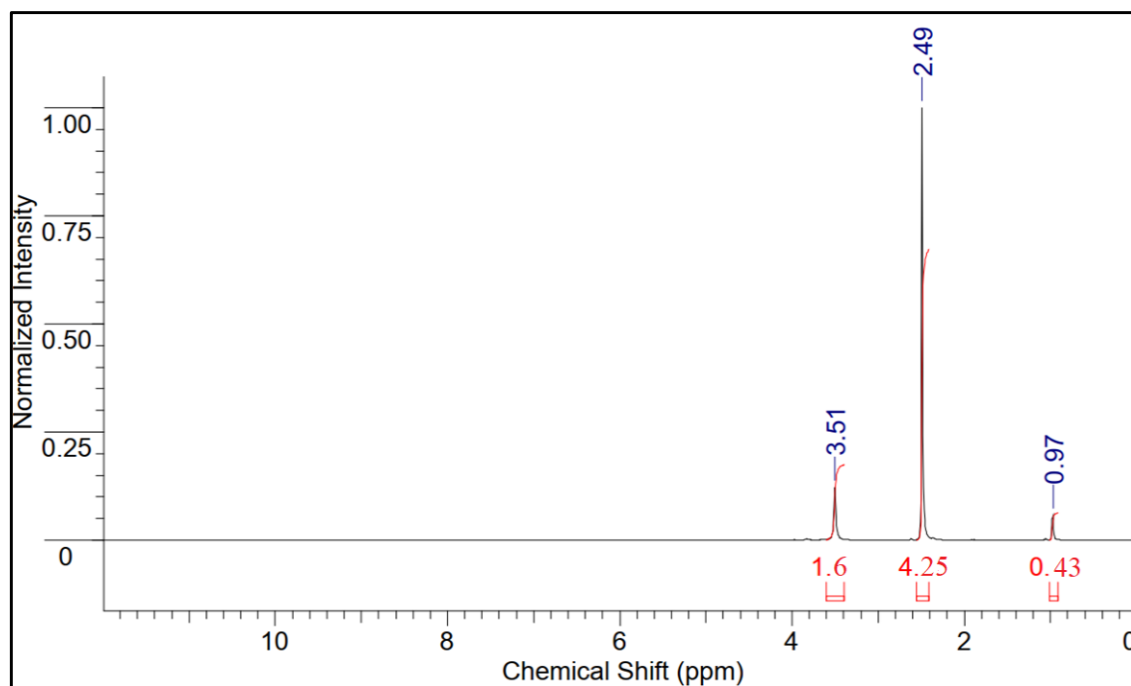


Figure 5. NMR ^1H spectrum of the complex.

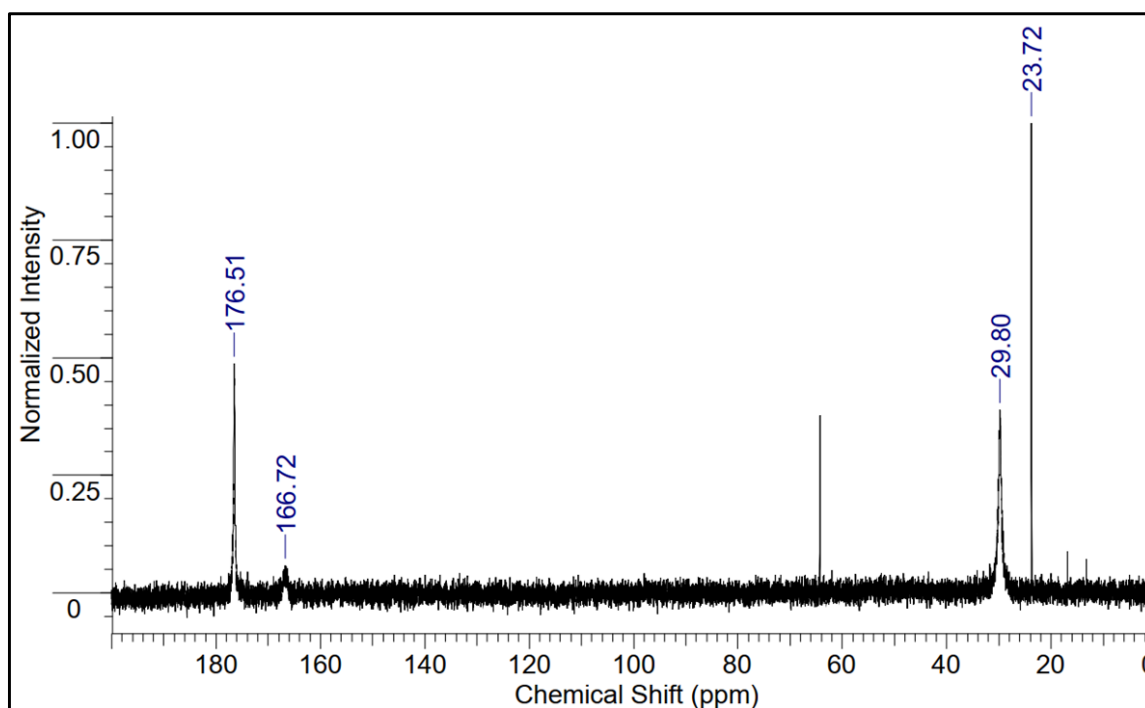


Figure 6. ^{13}C spectrum of the complex.

3.5. SEM Analysis

Figure 7 shows SEM images of the surface morphology of the $[\text{Cu}(\text{succ})(\text{gly})]$ complex, which is characterized by a pronounced layered structure (Figure 7a,b). It can be seen that the outer surface of the particles is smooth and well-formed. The cross-section indicates a sandwich structure formed by stacking plates with sharp edges of the crystal structure (Figure 7b,c). The thickness of each layer is 1500–2483 microns. The interlayer space is 3522–4480 (Figure 7d–f).

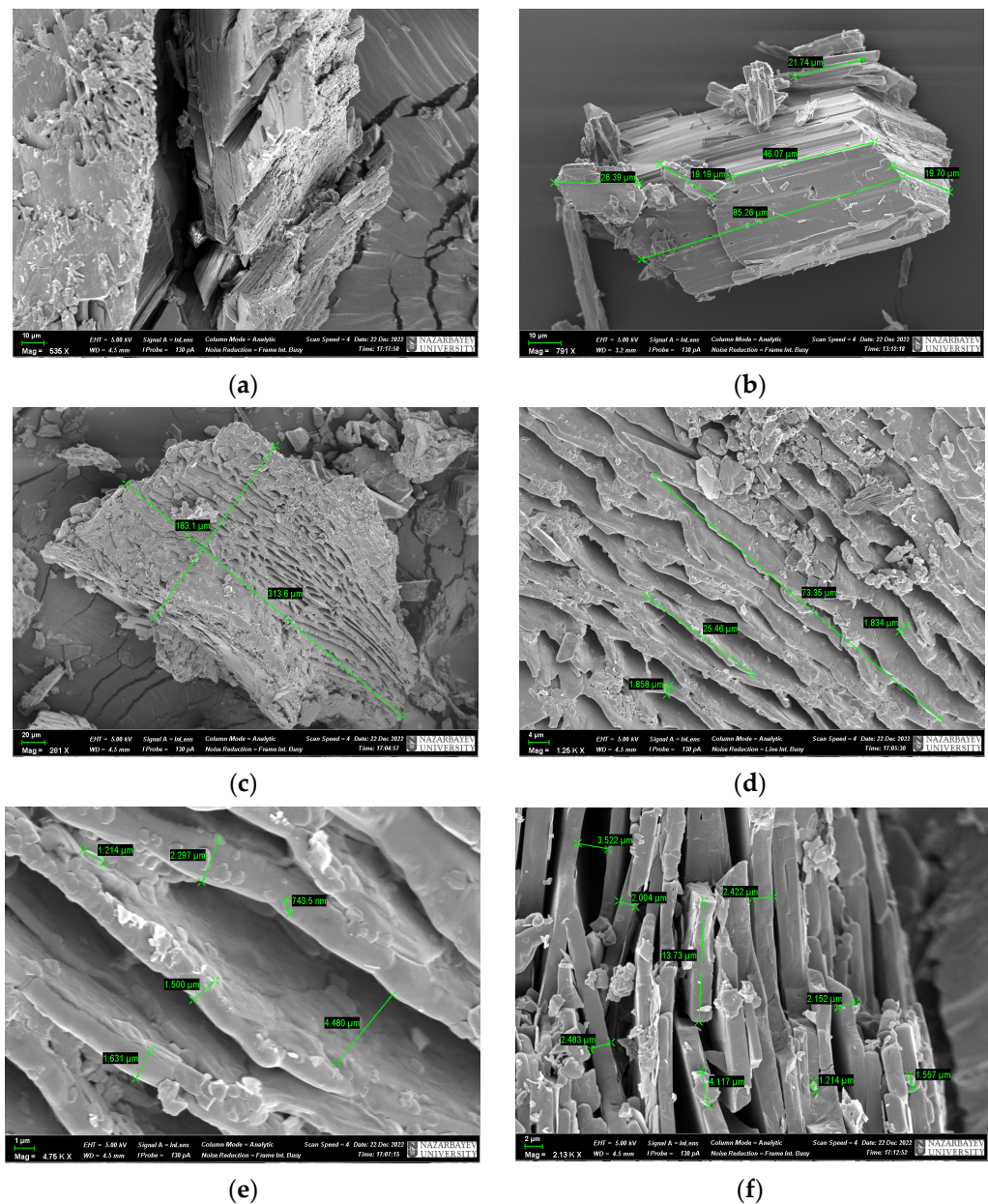


Figure 7. SEM images of the complex $[\text{Cu}(\text{succ})(\text{gly})]_n$. (a,b) the layered structure of $[\text{Cu}(\text{succ})(\text{gly})]_n$, (c,d) the crystal structure of $[\text{Cu}(\text{succ})(\text{gly})]$, (e,f) The thickness and interlayer space.

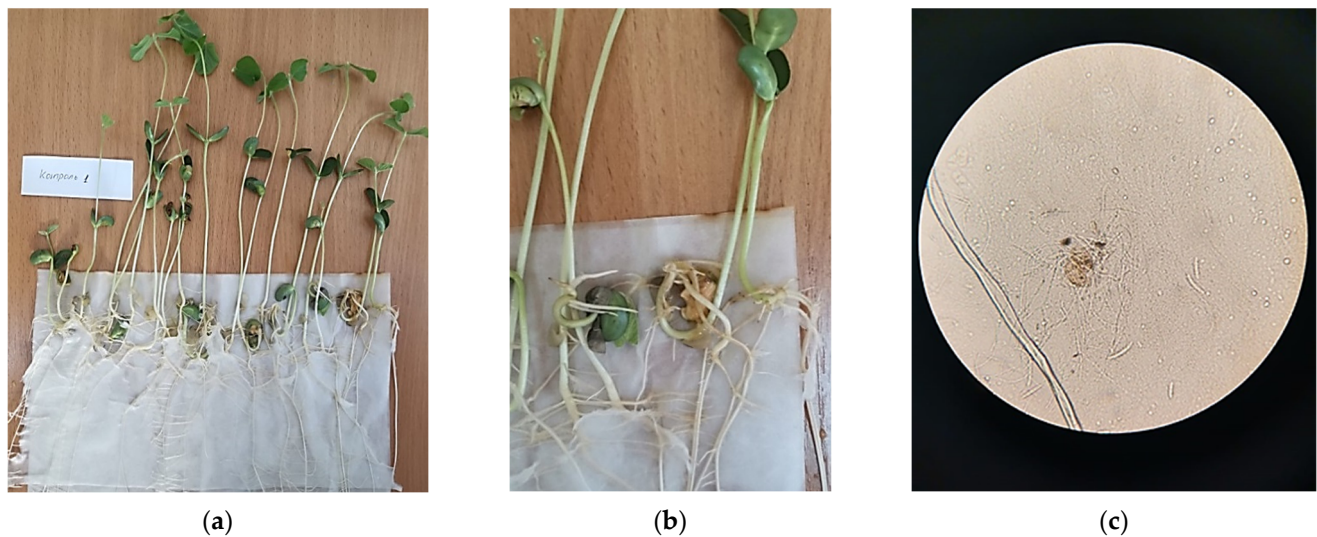
3.6. The Effectiveness of $[\text{Cu}(\text{succ})(\text{gly})]$ in Laboratory Conditions

A mycological analysis was carried out to study the effect of the complex on the germination and infection of the seeds of the soybean variety “Nur+”. The soybean seeds were grown using the $[\text{Cu}(\text{succ})(\text{gly})]$ complex and succinic acid by the roll method. For this, aqueous solutions of succinic acid and the complex, at a concentration of 5×10^{-3} mol/L, were prepared. Seeds grown in distilled water were used as control. The results of the average data are presented in Table 1.

Table 1. Viability and pathogens of soybean seeds before and after using the complex.

Sample	Viability, %		Pathogens, %			
	Germination	Outwardly Healthy	Alternariosis	Cercosporosis	Bacteriosis	Fusarium
Control	98.0 ± 2	63.3 ± 2	0	0	20.35 ± 2	16.4 ± 2
Succinic acid	100.0 ± 2	64.0 ± 2	0	0	22.0 ± 2	14.0 ± 2
[Cu(succ)(gly)]	100.0 ± 2	78.0 ± 2	0	0	12.0 ± 2	10.0 ± 2

The soybean seeds that were grown in distilled water showed an average germination rate of 98.0%. The bacteriosis damage was observed to be 20.35% and fusarium 16.4% (Table 1, Figure 8). Outwardly healthy seedlings are those seedlings on which, during the analysis, there were no browning spots or various lesions by pathogens, and which had correctly formed a root, stem, cotyledons, and leaves. Outwardly healthy seedlings were noted at 63.3%. Alternariosis and cercosporosis were absent.

**Figure 8.** Mycological analysis of soybean control samples: (a)—control sample germination; (b)—sprout affected by fusarium; (c)—fusarium spores at 10× magnification.

In the case of fusarium, dark necrosis was observed on the roots, the base of the hypocotyl, and the cotyledons.

The seeds grown in succinic acid at a concentration of 5×10^{-3} mol/L showed a germination rate of 100%. The defeat by bacteriosis was 22.0% and, by fusarium, 14.0% (Table 1, Figure 9). The percentage of outwardly healthy seedlings was 64.0%.

**Figure 9.** Cont.

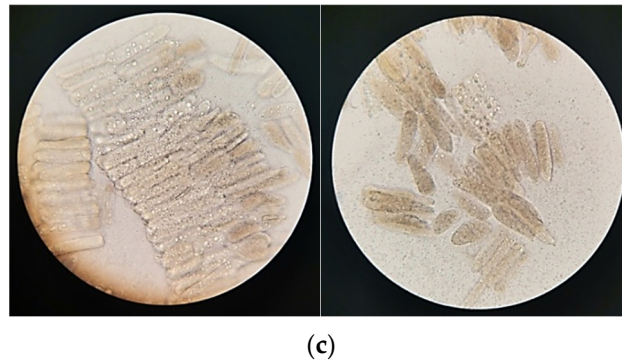


Figure 9. Mycological analysis of soybeans grown using a solution of succinic acid, 5×10^{-3} mol/L: (a)—general germination; (b)—sprouts affected by bacteriosis; (c)—soybean cotyledon cells destroyed by bacteriosis.

The most common causative agents of bacteriosis of soybean seed material are *Starr*, *Burkh*, and *Pseudomonas tabaci*. During the examination of the cotyledons of the seedlings, brown, gray, or dark gray spots of different sizes are observed, penetrating or deeply depressed, ulcerative, and soft. On the edge, the spots are brown or dark brown. On the hypocotyl genus, some seedlings have wide oblong light brown depressed streaks. The infectious onset can be not only on the surface of the seed but also in the depths of its tissue. With a strong degree of infection, the seeds rot, become covered with mucus, and emit an unpleasant odor.

The germination of seeds grown with the addition of the $[\text{Cu}(\text{succ})(\text{gly})]$ complex was 100%. The defeat by bacteriosis was 12.0% and by fusarium 10.0%. During the analysis, 78.0% of outwardly healthy seedlings were noted (Figure 10). Outwardly healthy seedlings have well-formed roots, stems, and cotyledons. Darkening and spots on the seedlings were absent.



Figure 10. Mycological analysis of seeds grown using the complex $[\text{Cu}(\text{succ})(\text{gly})]$.

The results of laboratory testing of the $[\text{Cu}(\text{succ})(\text{gly})]$ complex showed that seedlings that were grown using succinic acid and the $[\text{Cu}(\text{succ})(\text{gly})]$ complex had a higher germination rate than seedlings grown in water. Using the complex, outwardly healthy seedlings were noted to be 14.7% higher, and bacteriosis and fusarium decreased by 8.35% and 6.4%, respectively, compared with distilled water. This indicates the biological effectiveness of the synthesized $[\text{Cu}(\text{succ})(\text{gly})]$ complex in terms of increasing the germination rate and the number of healthy seeds. This is due to the fact that the copper in the composition of

the complex is in an active mobile form; accordingly, its properties are absorbed by the epidermal cells of the roots, transferred to the center of the roots through the parenchyma to endodermis, then loaded into the xylem and act as an indispensable cofactor for numerous proteins. On the other hand, glycine, as a protein component, can immediately be incorporated into the plant skeleton, strengthening cell walls, which limits the penetration of pathogens into plant tissues and, at the same time, increases both the transport of copper ions into the xylem and its absorption by the plant.

Within plants, “proteinogenic” amino acids serve multiple essential functions. Beyond their primary role in nitrogen uptake and transport, they also act as crucial signaling molecules, osmolytes (substances regulating osmotic pressure), and serve as precursors for the synthesis of various hormones, cofactors, and vital compounds like chlorophyll. Additionally, plants utilize amino acids to collectively produce a vast array of specialized compounds that facilitate ecological interactions and enable adaptive responses to environmental stresses. These diverse roles highlight the significance of amino acids in supporting the intricate and dynamic processes of plant life. The application of exogenous amino acids, peptides, and proteins offers more than just a positive impact on nitrogen metabolism. It suggests that these components extracted from the soil play various roles, leading to increased productivity, enhanced resistance to environmental stresses, and improved physiological traits across several agricultural species. Once amino acids and peptides breach the cuticular barrier, they gain access to the cell wall space (apoplast) and can be absorbed by specific transporters located on the plasma membrane [45].

Protective-stimulating complexes [Cu(succ)(gly)] protect plants by increasing disease resistance, changing the plant metabolism in a direction unfavorable for the pathogen, or limiting the development of the pathogen through competition. As a result of germination, the complex is able to increase the resistance of the protein-synthesizing and photosynthetic apparatus of the plant cell, the reproductive apparatus of plants. Many stresses cause the abscission of flowers and the plant’s ovaries. Under the influence of stress in plants, the formation of ethylene (the so-called stress ethylene) is enhanced; according to our data, in plant dynamics, plants treated with complexes in the composition [Cu (succ) (gly)] reduced the amount of stress ethylene. Enriching seeds and plants with copper has a noticeable effect on increasing the levels of free tryptophan, facilitating the absorption and accumulation of essential nutrients such as phosphorus and calcium. Copper’s involvement in seed germination processes is attributed to its provision of tryptophan, a crucial component in the synthesis of growth stimulants. Additionally, during this investigation, a more pronounced stimulating effect against succinic acid pathogens was observed when copper was combined with [Cu(succ)(gly)], as compared to using succinic acid alone to determine diseases.

The [Cu(succ)(gly)] complex mentioned above has demonstrated significant success, as its application enhances the vital activity of young plants, ensuring the availability of essential nutrients during the critical initial stages of growth [46].

Perhaps, this explains the increasing in apparently healthy seedlings by 14% and the decrease in pathogens to 10–12%, improving the energy metabolism in plants with succinic acid allowing to increase the germination and quality of soybeans, which were obtained by treating the plant separately with succinic acid and the complex.

4. Conclusions

A copper complex based on succinic acid and glycine of formula [Cu(succ)(gly)] was synthesized and characterized. Using the method of NMR spectroscopy, it was found that coordination is carried out through the nitrogen atoms of the amino group and oxygen of the carboxyl group of glycine, and two oxygen atoms of the carboxyl group of succinic acid. The XRD diffraction pattern determined the crystal structure of the obtained complex with a pronounced layered structure. Mycological analysis of soybean seeds of the “Nur+” variety showed that [Cu(succ)(gly)] can significantly reduce the number of pathogens, in particular bacteriosis and fusarium by 8.35% compared with the control and separately with succinic

acid. In addition, the synthesized heteroleptic complex did not show phytotoxicity in relation to plants and increased the germination of soybeans to 100% and healthy seedlings by 14.7%. Therefore, the heteroleptic complex [Cu(succ)(gly)] with a clear antipathogenic effect and safety for plants has great potential for crop protection and can be used both in pre-sowing seed treatment and in feeding in all phases of plant vegetation.

The usage of non-toxic and biodegradable chelating agents in the development of [Cu(succ)(gly)] contributed to the production of a “green” heteroleptic copper complex with a fungicidal and stimulating effect. Moreover, this complex has a great potential for sustainable crop protection.

Author Contributions: Conceptualization, S.K. and S.T.; methodology, K.S.J., N.H. and E.S.; software, K.A.; validation, A.K., M.B. and E.S.; formal analysis, B.S.S.; investigation, A.K. and K.A.; data curation, S.K. and S.T.; writing—original draft preparation, A.K.; writing—review and editing, S.K. and S.T.; visualization, B.S.S. and K.A.; supervision, S.K. and B.S.S.; project administration, S.K.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

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Conflicts of Interest: The authors declare no conflict of interest.

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