



Efficacy of the “Complex-Co” plant growth stimulator and micronutrient complex preparation against selected phytopathogens and postharvest spoilage fungi

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ABSTRACT

Background: The growing emphasis on sustainable agriculture has intensified interest in plant growth stimulants derived from natural, non-toxic components. Among these innovations is the micronutrient formulation “Complex-Co,” a tartaric acid-based chelate containing vital elements such as iron (Fe), copper (Cu), zinc (Zn), and boron (B). These micronutrients play key roles in plant physiology, including enzyme function, photosynthesis, growth regulation, and stress tolerance. As a plant growth stimulant, “Complex-Co” holds promise for enhancing plant vigor and strengthening resistance against phytopathogenic and postharvest spoilage fungi, major contributors to reduced crop yields and quality deterioration.

This study is the first to evaluate the antifungal potential of the multifunctional Complex-Co formulation, which combines copper, zinc, and iron with a biogenic nitrogen-containing tartaric acid derivative. Its unique composition

enables simultaneous stimulation of plant growth and inhibition of key postharvest phytopathogens, highlighting its potential for sustainable crop protection and functional-food applications.

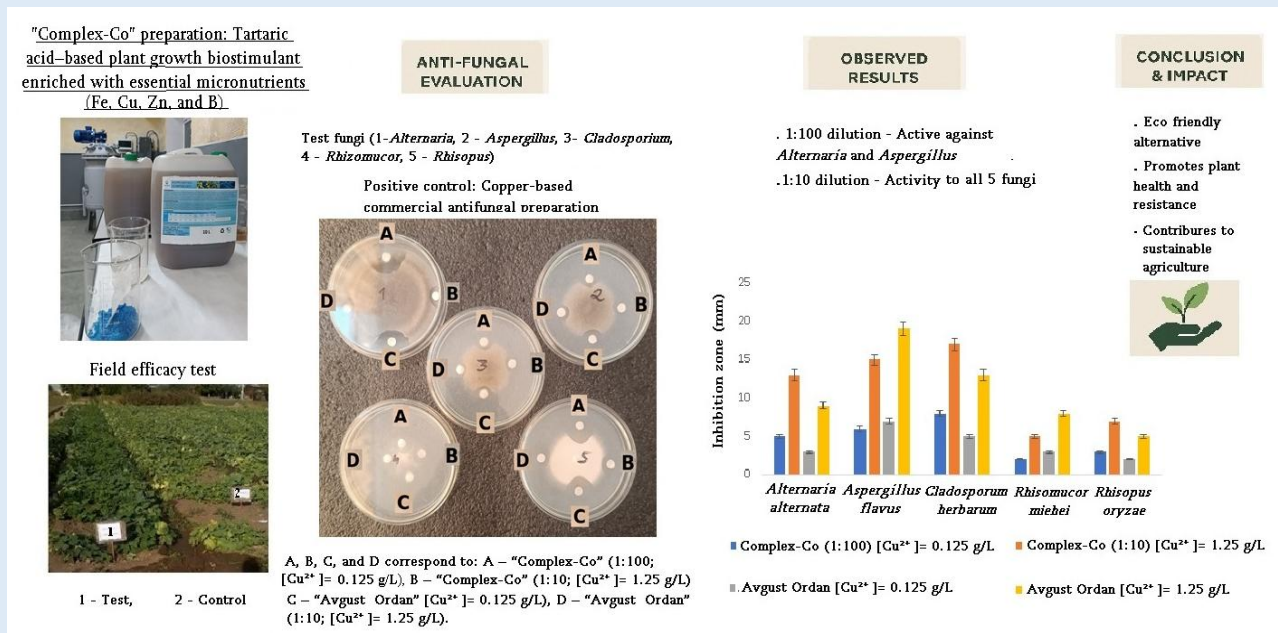
Objective: This study aims to investigate the antifungal efficacy of the micronutrient-based plant growth promoter “Complex-Co” against selected phytopathogenic and postharvest spoilage fungi. The research evaluates explicitly the antifungal activity of the formulation at concentrations commonly used in standard plant nutrition practices. Furthermore, the study compares the effectiveness of “Complex-Co” with that of conventional copper-based antifungal treatments.

Materials and Methods: To assess antifungal activity, fungal strains from the genera *Alternaria*, *Aspergillus*, *Cladosporium*, *Rhizomucor*, and *Rhizopus* were used as test organisms. Cultures were grown on potato dextrose agar (PDA) in 90 mm × 15 mm Petri dishes and incubated at 25 ± 1 °C. Once the fungal mycelia reached a diameter of 4-5cm, four sterile filter paper disks (6 mm in diameter) were placed approximately 5mm from the edge of the colony. The “Complex-Co” preparation was tested at 10-fold and 100-fold dilutions, alongside a similarly diluted copper-based antifungal formulation for comparison. Each disk was treated with 20 µL of the respective solution. Following treatment, the plates were incubated at 25°C, and fungal growth inhibition was monitored for 2 to 7 days.

Results: The antifungal activity of “Complex-Co” was evaluated against five phytopathogenic fungi: *Alternaria alternata*, *Aspergillus flavus*, *Cladosporium herbarum*, *Rhizomucor miehei*, and *Rhizopus oryzae*. At a 1:100 dilution, which corresponds to a Cu^{2+} concentration of 0.125 g/L, inhibition was limited, with zones ≤ 8 mm. At a 1:10 dilution ($[\text{Cu}^{2+}] = 1.25$ g/L), antifungal activity increased markedly, particularly against *Alternaria alternata* (13 mm), *Aspergillus flavus* (15 mm), and *Cladosporium herbarum* (17 mm). Compared with the commercial fungicide “Avgust Ordan” at equivalent copper concentrations, “Complex-Co” showed comparable or superior inhibition against certain fungi. UV-Visible spectroscopy confirmed the presence of proteinaceous and amino acid components, suggesting their roles in copper chelation, solubility, stabilization, and enhanced antifungal activity. These results demonstrate a concentration-dependent antifungal activity and highlight the potential of “Complex-Co” as a multifunctional plant protection and nutrient formulation.

Conclusion: Micronutrient “Complex-Co” is demonstrating its potential as a broad-spectrum, environmentally friendly alternative to chemical antifungal treatments. The formulation, which includes essential micronutrients, not only promotes plant growth but also enhances resistance to fungal pathogens. This can reduce reliance on synthetic pesticides, improve crop quality, and increase food security, offering a sustainable solution for both agricultural productivity and public health.

Keywords: Chelated Micronutrient, Natural Tartaric Acid, Antifungal Activity, Sustainable Agriculture, Postharvest spoilage fungi.



Graphical Abstract: Efficacy of the "Complex-Co" Plant Growth Stimulator and Micronutrient Complex Preparation Against Selected Phytopathogens and Postharvest Spoilage Fungi

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INTRODUCTION

The shift toward sustainable green agriculture, particularly through the integration of waste management technologies, has become a critical global objective in the 21st century. Aligned with the priorities of the Sixth Session of the United Nations Environment Assembly (UNEA-6) (<https://www.unep.org/environmentassembly/unea6>), many national programs now focus on scientific and technological innovations that advance a circular economy and support sustainable development goals. A central strategy in this transition is the valorization of secondary raw materials in agricultural production systems to reduce the ecological footprint of synthetic agrochemicals [1-2].

In this context, the development of environmentally safe agricultural inputs such as plant growth stimulants,

bio-based fertilizers, and integrated plant protection agents derived from renewable natural resources and agro-industrial by-products has attracted significant attention [3]. These next-generation formulations offer effective, non-toxic alternatives to conventional chemical pesticides, which are often associated with adverse environmental and health impacts, including harm to beneficial organisms, disruption of soil microbiota, and accumulation of hazardous residues in food products [4-5]. Designing agrochemicals that are both effective and biodegradable represents a pressing scientific challenge with broad ecological and public health implications [6]. Natural bioactive compounds, whether nutritive or non-nutritive, play crucial roles in plant defense, growth regulation, and stress tolerance, making them attractive candidates for sustainable plant protection. In agricultural biotechnology, their biocompatibility,

multifunctionality, and potential for targeted action are highly valued [7-8].

Bioactive compounds are increasingly recognized in functional foods and sustainable agriculture for their physiological effects, safety, and multifunctionality. According to this approach, bioactive compounds—whether nutritive or non-nutritive—are considered valuable not only for plant growth and defense but also for their role in supporting food quality and human health when present in crop-derived products. Integrating these compounds into plant protection strategies ensures that agrochemical innovations remain consistent with functional food principles, promoting both environmental sustainability and consumer safety [9].

Recent advances in bioorganic and medicinal chemistry have further revealed that amide and imide derivatives of dicarboxylic acids, such as tartaric, succinic, and maleic acids, possess potent antimicrobial activity, attributed to their ability to disrupt microbial cell walls, inhibit essential enzymes, and alter membrane permeability [10-11]. Tartaric acid derivatives, including mono- and di-amides, exhibit enhanced binding to microbial membrane proteins via hydrogen bonding and hydrophobic interactions [12]. Their activity can be optimized by introducing aromatic, heterocyclic, or alkyl substituents at the amide nitrogen, thereby improving lipophilicity and cellular uptake. In addition, it is well known that organic acid imide derivatives effectively inhibit fungal spore germination and bacterial growth by interfering with cell wall biosynthesis, DNA replication, and oxidative stress pathways [13].

Moreover, incorporating nitrogen-containing functional groups into the tartaric acid backbone enhances antimicrobial potential and enables synergistic effects when combined with metal complexes. These hybrid metal-organic structures can provide multi-targeted pathogen control while reducing the risk of

resistance development. The appeal of tartaric acid lies in its biodegradability, non-toxicity, and ready availability from winemaking and agro-industrial waste, making it an ideal platform for green chemistry synthesis and eco-agriculture applications [14]. Numerous organic acids and their salts are recognized as safe for consumption and are classified as Generally Recognized as Safe (GRAS) under FDA regulations. Beyond their safety, these compounds are widely employed in food preservation, serving roles as acidulants, antioxidants, flavor enhancers, pH regulators, and nutrient contributors. They participate in various processes, including biochemical metabolism, hydrolysis, and microbial activity, to maintain food quality and stability [15, 16].

Notably, amino derivatives of tartaric acid, such as mono-/di-amides and polyamides, have demonstrated high bactericidal activity against *Escherichia coli*, *Pseudomonas aeruginosa*, *Shigella* spp., *Salmonella typhi*, *Bacillus subtilis*, *Bacillus cereus*, and the pathogenic fungus *Trichophyton rubrum* [17].

Recent studies in functional food science emphasize that bioactive phytochemicals—especially organic acids, phenolic derivatives, and nitrogen-containing metabolites—play a crucial dual role by contributing both to plant protection and to the safety of crop-derived foods [18–19]. Many antifungal phytochemicals naturally accumulated in plants act as protective secondary metabolites that suppress the growth of toxin-producing fungi such as *Aspergillus*, *Fusarium*, and *Penicillium* species, thereby reducing the risk of mycotoxin contamination along the food supply chain [20]. This integrative perspective aligns with the principles of functional foods, which require that agricultural inputs enhance plant health while safeguarding the nutritional and hygienic quality of harvested products. Accordingly, the development of eco-friendly antimicrobial agents based on tartaric acid derivatives offers a promising route toward improving both crop resilience and downstream

food safety, positioning these compounds as potential contributors to sustainable functional-food systems.

MATERIALS AND METHODS

Over the past decade, our research team [21] has developed and tested a series of plant growth-promoting and micronutrient-enriched formulations, collectively referred to as the “Complex” series, in field trials. These formulations are derived from natural by-products of winemaking, specifically wine tartar (potassium bitartrate) and vine yeast biomass sediments. The series includes variants with added functionalities, such as “Complex Plus” (with insecticidal properties) and “Complex-Co” (with antibacterial and antifungal activity). These preparations are environmentally safe, non-toxic to humans, and produced using an affordable, waste-free technology.

The formulation investigated in this study, “Complex-Co,” is a plant growth biostimulant enriched with essential micronutrients and designed to promote crop development while providing antimicrobial protection. It is produced through controlled chemical processing of potassium bitartrate, a naturally occurring compound obtained from winemaking by-products. It is fortified with trace elements including iron (Fe), copper (Cu), zinc (Zn), and boron (B). The manufacturing process has been optimized to ensure batch-to-batch consistency, and representative experimental lots have undergone laboratory-scale microbiological and toxicological evaluations. These were followed by field

trials to assess agronomic performance and antimicrobial efficacy [22-23].

In addition to its inorganic constituents, “Complex-Co” incorporates biologically derived organic compounds, primarily amino acids and proteins sourced from yeast biomass sediments co-precipitated with wine tartar, a valuable by-product of winemaking. During the production process, these biomolecules, naturally present at concentrations of 1.7 g/L for amino acids and 2.15 g/L for proteins, are solubilized into the liquid phase. Their presence is hypothesized to serve a dual function: stabilizing metal ions within the formulation and enhancing its biostimulant efficacy, while simultaneously contributing to its protective effects against phytopathogenic microorganisms.

The formulation is produced via a waste-free, low-energy synthesis route for chelated metal complexes of Cu^{2+} , Zn^{2+} , and Fe^{2+} , employing naturally occurring tartaric acid as the primary ligand. Furthermore, nitrogen-enriched bioactive derivatives are introduced via the chemical modification of tartaric acid with ethanolamine (colamine), yielding ethanolamine complex salts of tartaric acid (EACS). These compounds have been previously evaluated as antioxidants and anti-spoilage additives for the fish product industry [24]. Within the context of the “Complex-Co” formulation, EACS was investigated as a potential active ingredient with fungicidal properties to identify effective candidates for the development of novel biologically active agents suitable for sustainable crop protection. The composition and some physicochemical parameters of the “Complex-Co” preparation are shown in Table 1.

Table 1. Elementary and organic composition of the “Complex-Co” preparation (g/L)

Elementary consistence g/L						Biogenic sourced organic compounds g/L				Physical characteristics	
Fe	Zn	Cu	B	K	SO_4^{2-}	Tartaric acid	EACS	Amino acids	Proteins	pH	Density g/L
6.1	8.7	12.5	5	27.8	78.9	17	2.5	1.7	2.15	3.6	1310

UV/VIS Spectral Analysis of the “Complex-Co” Preparation: Total Protein and Amino Acid Assay: The

amino acid concentration in the “Complex-Co” preparation was determined using the ortho-

phthalaldehyde (OPA) method [25-26]. The OPA reagent was prepared in 0.2 M borate buffer (pH 9.7) and contained 0.1667mg/mL OPA and 1.18 mM mercaptoethanol. For analysis, 50µL of the preparation was mixed with 1.5mL of OPA reagent and 1.5mL of distilled water. A 10 mM aqueous methionine solution was used to determine the extinction coefficient. Following a 5-minute incubation at room temperature, absorbance was recorded at 340nm using a Thermo Scientific Genesys 50 VIS/UV-Vis spectrophotometer. Total protein content was quantified according to the method of Groves and Davis [27].

Antifungal Activity Assay: Fungal Strains and Culture

Conditions: To evaluate the antifungal activity of the “Complex-Co” plant growth-promoting and micronutrient preparation, *in vitro* tests were conducted using phytopathogenic fungi belonging to the genera *Alternaria*, *Aspergillus*, *Cladosporium*, *Rhizomucor*, and *Rhizopus*. These genera were selected based on their prevalence and relevance in postharvest spoilage and economically significant plant diseases [28]. For example, *Alternaria* species can cause leaf blotch, fruit spot, and early blight in crops such as apple and tomato. [29] *Aspergillus spp.* are often implicated in storage rots of nuts, cereals, and fruits. *Cladosporium* species cause leaf spot and soft rot diseases in vegetables and ornamentals. Members of *Rhizomucor* and *Rhizopus*, particularly *Rhizopus stolonifer*, are well known to cause soft rot (mucoralean spoilage) in a wide range of fruits and vegetables during storage (e.g., in sweet potato) [30]. The fungal strains were obtained from the Microbial Depository Center (MDC) of the Scientific and Production Center “Armbiotechnology” NAS RA. The following strains were used: *Alternaria alternata* MDC 8126, *Aspergillus flavus* MDC 10561, *Cladosporium herbarum* MDC 8270, *Mucor miehei* MDC 1365, and *Rhizopus oryzae* MDC 10709
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[blocks/December2021/i7QnHB4VnIPYaoSF576p.pdf](https://armbiotech.am/uploads/pdf-blocks/December2021/i7QnHB4VnIPYaoSF576p.pdf)]. All strains were maintained on potato dextrose agar (PDA) before experimentation [31].

For culturing, first-generation colonies were spread onto fresh PDA plates (90mm diameter, 15 mm depth; Biolab, Budapest, Hungary) containing 20.0 g/L glucose, 4 g/L potato extract, and 18 g/L agar. The media were sterilized by autoclaving at 121°C for 15 minutes before pouring. The plates were incubated in the dark at 25±1°C for 5-7 days to promote active mycelial growth.

Disk Diffusion Method for Antifungal Testing: When the fungal colonies reached a diameter of approximately 30-40mm, sterile paper disks (6 mm in diameter) were aseptically placed equidistantly (about 5mm) from the edge of the fungal colony.

The following test solutions were used: “Complex-Co” formulation diluted in sterile distilled water at 1:10 and 1:100 (v/v). The initial “Complex-Co” formulation contained 12.5 g/L of Cu²⁺ in a 0.9% NaCl solution, serving as the negative control.

As a positive control, the commercial fungicide “Avgust Ordan” WP (wetable powder) was used. This product is manufactured by “Avgust” CJSC (Russian Federation; <https://avgust.com/en/>). The formulation contains two active ingredients: copper oxychloride (CAS No. 1332-40-7) at 689 g/kg and cymoxanil (CAS No. 57966-95-7), an acetamide derivative with both curative and preventive foliar fungicidal activity, at 42 g/kg. Based on its mode of penetration, Ordan is classified as a fungicide with both contact and systemic action, while functionally it acts as a protective and curative agent. This two-component fungicide is widely used to protect potatoes, tomatoes, cucumbers, onions, and grapes against a broad spectrum of diseases, including late blight and early blight (*Alternaria*) in potatoes and tomatoes, downy mildew (*Peronospora*) in cucumbers and onions,

and grapevine mildew (*Plasmopara viticola*). Application rates vary depending on the crop and pathogen. Still, the average recommended dose is 2.5 kg/ha, applied as an aqueous suspension at 500 L/ha (<https://en.gardeniadream.com/21333122-fungicide-ordan-instructions-for-use-and-composition-how-to-breed-and-analogues>). At this dosage, the working solution corresponds to approximately a 200-fold dilution, providing a copper oxychloride concentration of 3.425 g/L, which in terms of elemental copper content equals 2.05 g/L. During the evaluation of the antifungal effect, the “Avgust Ordan” preparation was tested at copper concentrations of 1.25 g/L and 0.125 g/L to ensure comparability with “Complex-Co”.

Each disk received 20 μ L of the respective solution using a micropipette. After application, plates were incubated at 25 \pm 1 $^{\circ}$ C for 2 to 7 days, and the inhibition zones were subsequently measured.

Evaluation of Inhibitory Effect: Fungal growth inhibition was monitored by observing clear zones around the disks. The diameter of the inhibition zone was measured in millimeters using a ruler or a caliper. The mean zone size was calculated from three replicates.

Absence of a zone indicated no activity, while inhibition zones greater than 2mm were considered evidence of antifungal potential. The entire experiment was performed in triplicate for reproducibility.

Statistical Analysis: All experiments were performed in 5 series, with 3 repeats per probe. Microsoft Excel 2016 was used to analyze the antifungal effects of “Complex-Co” preparations. Data on growth inhibition zones are given in mm (Figure 1, Table 2). Significance was tested using the Student t-test and was considered significant if

the p-value was less than 0.05. Results are presented as the mean \pm standard deviation (SD).

RESULTS

UV-Visible Absorption Spectrum of Complex-Co: The UV-Visible absorption spectrum of the “Complex-Co” preparation was recorded in the range of 200–800nm (Figure 1). The spectrum showed markedly high absorbance values in the 210-230 nm region, corresponding to strong absorption by peptide bonds and other chromophoric groups of organic biomolecules. A relative minimum was observed around 250nm, followed by a pronounced absorption peak at 280nm (Abs \approx 1.79). This spectral feature is characteristic of aromatic amino acids (tryptophan, tyrosine, and phenylalanine) and proteinaceous components, thereby confirming the presence of yeast-derived proteins and amino acids within the preparation. Beyond 300nm, the absorbance values gradually decreased, and no significant absorption was detected throughout the visible spectrum up to 800nm [32].

Figure 1. UV-Visible absorption spectrum of the “Complex-Co” preparation. These results indicate that the organic fraction of “Complex-Co”, composed of amino acids and proteins, remains soluble and spectrally detectable after dilution (1:100). The observed absorption profile supports the proposed dual functionality of these biomolecules: stabilization of metal ions in the formulation.

In vitro Antifungal Activity Against Phytopathogens, the antifungal activity of the tested preparations was assessed by measuring the inhibition zones formed around filter paper disks in contact with actively growing fungal mycelia. The mean diameters of inhibition zones are summarized in Table 2.

Table 2. Comparative antifungal activity of “Complex-Co” and Avgust Ordan against phytopathogenic fungi. *Values represent mean inhibition zone diameters (mm) observed after 2-7 days of incubation.

Fungal strain	“Complex-Co” (1:100) [Cu ²⁺]-0.125g/L	“Complex-Co” (1:10) [Cu ²⁺]-1.25g/L	“Avgust Ordan” [Cu ²⁺]- 0.125g/L	“Avgust Ordan” [Cu ²⁺]-1.25g/L
<i>Alternaria alternata</i>	5 ± 0,21mm	13 ± 0.67 mm	9 ± 0,44mm	15 ± 0,73mm
<i>Aspergillus flavus</i>	6 ± 0.32mm	15 ± 0.78mm	7 ± 0,36mm	19 ± 0,86mm
<i>Cladosporium herbarum</i>	8 ± 0.39mm	17 ± 0,64mm	5 ± 0,27mm	13 ± 0.51mm
<i>Rhizomucor miehei</i>	2 ± 0,11mm	5 ± 0,25mm	3 ± 0.18mm	8 ± 0,43mm
<i>Rhizopus oryzae</i>	5 ± 0.24mm	13 ± 0,71mm	3 ± 0,22mm	9 ± 0,47mm

The microfertilizer “Complex-Co” demonstrated an apparent concentration-dependent antifungal effect. At the lower concentration (1:100; [Cu²⁺]= 0.125 g/L), inhibition was weak for most fungi, with zones not exceeding 8 mm. In contrast, at the higher concentration (1:10; [Cu²⁺]= 1.25 g/L), “Complex-Co” exhibited more potent antifungal activity, particularly against *Alternaria*

alternata (13 mm), *Aspergillus flavus* (15 mm), and *Cladosporium herbarum* (17 mm).

The commercial fungicide Avgust Ordan, used as a positive control, showed the highest activity against *Aspergillus flavus* (19 mm) and *Alternaria alternata* (15 mm). In comparison, its effect on mucoralean fungi (*Rhizomucor miehei* and *Rhizopus oryzae*) was comparatively moderate (8 mm and 9 mm, respectively).

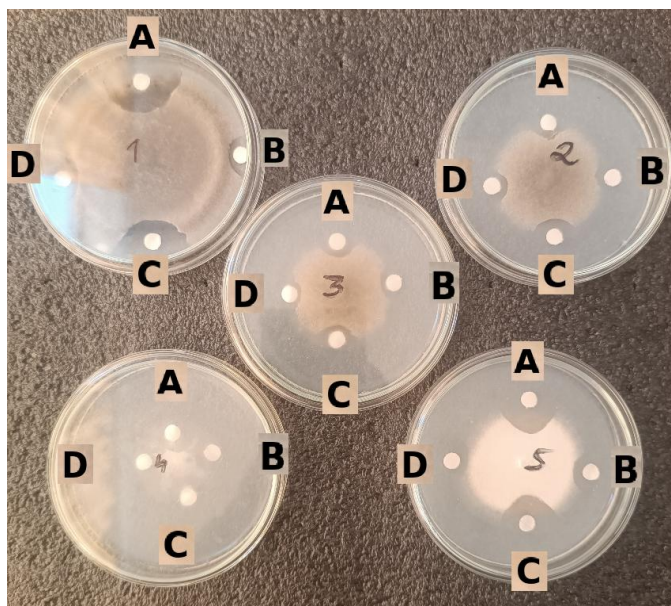


Figure 2. Antifungal activity of “Complex-Co” and “Avgust Ordan” against phytopathogenic fungi

Overall, the results indicate that “Complex-Co”, at equivalent copper concentrations, demonstrated comparable or in some cases stronger inhibitory effects than “Avgust Ordan”, especially against *Cladosporium herbarum* and *Alternaria alternata*.

Petri dishes show (1) *Alternaria alternata*, (2) *Aspergillus flavus*, (3) *Cladosporium herbarum*, (4) *Rhizomucor miehei*, and (5) *Rhizopus oryzae*. Disks A, B, C, and D correspond to: A – “Complex-Co” (1:100; [Cu²⁺]= 0.125 g/L), B – “Complex-Co” (1:10; [Cu²⁺]= 1.25 g/L), C –

“Avgust Ordan” (1:100; [Cu²⁺]= 0.125 g/L), and D – “Avgust Ordan” (1:10; [Cu²⁺]= 1.25 g/L).

Overall, these findings highlight that the antifungal activity of “Complex-Co” is strongly dose-dependent and, at higher concentrations, can reach or even exceed that

of the commercial fungicide “Avgust Ordan” for certain fungal strains. To better visualize these comparative results, the inhibition zone diameters are graphically summarized below.

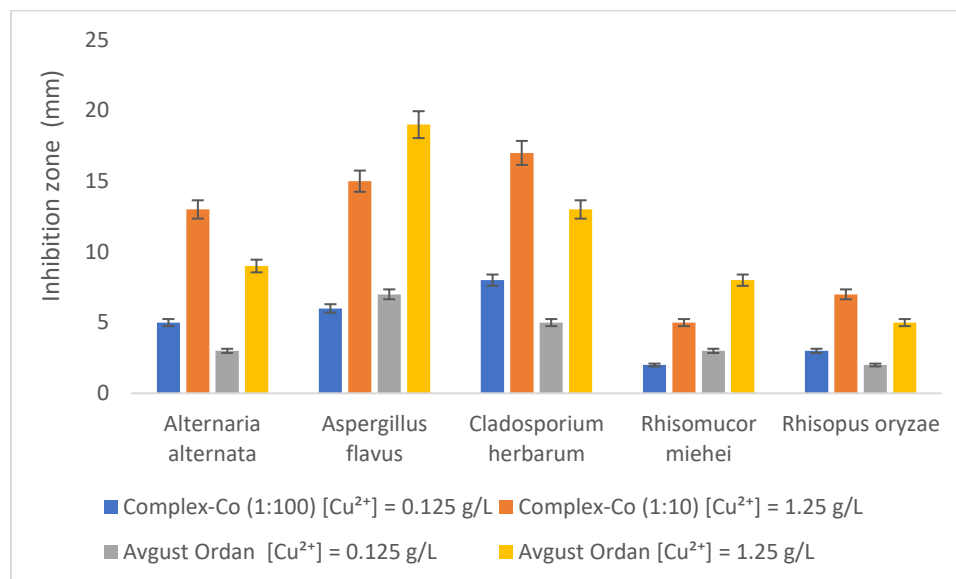


Figure 3. Illustrates the comparative antifungal activity of “Complex-Co” and “Avgust Ordan” against the tested fungi, expressed as inhibition zone diameters (mm)

DISCUSSION

This study evaluated the potential synergistic antifungal activity of the active components of organic chelated copper together with other essential metals, such as Zn and Fe, and the biogenic nitrogen-containing tartaric acid derivative ethanolamine complex salt (EACS), formulated as part of the multifunctional foliar fertilizer and plant biostimulant “Complex-Co”

Copper complexes with organic ligands have long been recognized as essential agents in agricultural chemistry for their dual roles in plant nutrition and protection. Copper is necessary for plants, as it participates in the synthesis of iron-containing enzymes and supports key physiological processes such as respiration, photosynthesis, carbohydrate metabolism, and the biosynthesis of vitamins B and P [33-34]. Moreover, copper readily forms highly stable complexes with amino acids, carboxylic acids [35-36], and

nitrogenous bases, thereby enhancing its bioavailability and biological activity [37-38].

Organic acids are increasingly valued in modern agriculture not only as growth-promoting agents but also as eco-friendly components that support metabolic functions and stress tolerance. In the context of global trends toward organic farming and the reduction of synthetic fertilizers and pesticides, the development of such multifunctional, biologically derived formulations is particularly relevant. Addressing the challenges of improving crop productivity while controlling phytopathogens requires adherence to the principles of green chemistry, emphasizing safety, sustainability, and environmental compatibility [39].

Within this framework, mixed-ligand complexes incorporating carboxylic acids, amino acids, and biogenic metals represent promising alternatives. Their advantages include accessibility, low production costs,

fungicidal activity, low toxicity, and easy biodegradability, which place them among the most effective and sustainable plant biostimulants. In this study, we highlight the antifungal potential of a novel mixed-ligand complex comprising tartaric acid, ethanolamine, amino acids, and copper, designed as a fungicidal biostimulant that substantially reduces pathogen loads while simultaneously promoting plant growth.

The in vitro antifungal assay clearly demonstrated a concentration-dependent activity of “Complex-Co”. At the lower dilution (1:100; [Cu²⁺] 0.125 g/L), growth inhibition of the tested phytopathogens was generally weak (≤ 8 mm). However, at the higher concentration (1:10; [Cu²⁺] 1.25 g/L), “Complex-Co” exhibited markedly more vigorous antifungal activity, with inhibition zones reaching 13–17 mm against *Alternaria alternata*, *Aspergillus flavus*, and *Cladosporium herbarum*. These results suggest that the formulation has the potential to function not only as a plant growth stimulant but also as a protective agent under field conditions.

When compared with the commercial fungicide August Ordan (copper oxychloride + cymoxanil), “Complex-Co” showed comparable or even superior inhibition against certain fungi. For example, while Ordan was most effective against *Aspergillus flavus* (19 mm) and *Alternaria alternata* (15 mm), “Complex-Co” demonstrated more potent inhibition against *Cladosporium herbarum* (17 mm vs. 13 mm). Interestingly, both products were less effective against mucoralean fungi (*Rhizomucor miehei* and *Rhizopus oryzae*), indicating that these genera may be less sensitive to copper-based treatments.

Taken together, these results indicate that the antifungal effect of “Complex-Co” is not solely attributable to copper ions but likely enhanced by its mixed-ligand composition, including tartaric acid, ethanolamine, and amino acids. This synergistic interaction may provide a broader spectrum of activity and improved environmental compatibility compared

with conventional copper fungicides. Therefore, “Complex-Co” can be considered a promising candidate for integration into sustainable crop protection strategies, particularly in systems aiming to reduce reliance on synthetic fungicides. Additionally, the antifungal activity of “Complex-Co” highlights its potential role as a bioactive, plant-derived formulation that supports sustainable agricultural practices. By reducing pathogen loads on crops, the preparation may help preserve the nutritional quality and overall safety of harvested products. These findings align with the principles of functional food science, in which biologically active compounds contribute not only to plant health but also to improved food quality throughout the supply chain. Incorporating such eco-friendly, multifunctional formulations offers a promising strategy for bridging crop protection with functional-food production.

CONCLUSION

The findings of this study highlight the novelty of the multifunctional microfertilizer “Complex-Co,” which combines organic chelated copper with amino acids, tartaric acid, ethanolamine, and other essential biogenic metals. Spectroscopic analyses confirmed the presence of proteinaceous and amino acid components, which not only stabilize metal ions but also enhance the formulation's bioactivity. This dual functionality—nutritional support and antifungal protection—sets “Complex-Co” apart from conventional copper-based fungicides. The observed concentration-dependent inhibition of major phytopathogens, including *Alternaria alternata*, *Aspergillus flavus*, and *Cladosporium herbarum*, underscores the potential of this preparation as an innovative tool that merges plant biostimulation with effective pathogen control.

From an applied perspective, “Complex-Co” demonstrated antifungal efficacy comparable to, and in some cases exceeding, that of the commercial fungicide “August Ordan”. Its synergistic composition likely

contributes to a broader spectrum of biological activity while maintaining eco-friendly properties, low toxicity, and biodegradability. These findings support the relevance of multifunctional bioactive formulations, such as “Complex-Co”, in promoting sustainable crop protection while maintaining the nutritional and functional quality of harvested products. These attributes make it a promising candidate for integration into sustainable agricultural practices, particularly in organic and low-input farming systems seeking alternatives to synthetic pesticides. By simultaneously supporting plant growth and reducing pathogen burden, “Complex-Co” represents a forward-looking strategy aligned with the principles of green chemistry and sustainable crop protection.

Abbreviations: ANAU: Armenian National Agrarian University, UNEA-6: Sixth Session of the United Nations Environment Assembly), SPC: Scientific and Production Center, NAS RA: National Academy of Sciences of the Republic of Armenia, MDC: Microbial Depository Center, EACS: ethanolamine complex salts of tartaric acid, PDA: potato dextrose agar, OPA: ortho-phthalaldehyde, ; GRAS Generally Recognized as Safe, FDA: Food and Drug Administration. DNA: Deoxyribonucleic acid, SD: Standard deviation, WP: Wettable Powder, CAS: Chemical Abstracts Service.

Conflicts of interest: The authors have no conflicts of interest to declare

Author Contributions: Conceptualization, A.M., Methodology, T. S., A.G., N.A., G.O., N. K., Software, T. E., Validation, A.A, V.B, Resources, A. M, V.B, Formal analysis, T.S., T.E., A.G., N.A., G.O., N.K., Writing—review & editing, A.M, T.S., V.G., All authors have read and agreed to the published version of the manuscript.

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