



Unravelling How Fungicides Affect the Absorption of Fertilizers by Soybean Leaves

Higor José Freitas Alves da Silva¹ · Eduardo Santos¹ · Gabriel Sgarbiero Montanha^{1,2} · Vinícius Pires Rezende¹ ·
Nícolas Gustavo da Cruz da Silva¹ · Julia Rossatto Brandão¹ · Eduardo de Almeida¹ ·
Hudson Wallace Pereira de Carvalho^{1,3} 

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Abstract

Purpose This study aimed to investigate the influence of a mix of manganese (Mn) and zinc (Zn) from soluble foliar fertilizers-based sulfates and EDTA chelates with fungicides-based emulsifiable concentrate and suspension concentrate for Powdery Mildew control.

Methods From greenhouse conditions, nutrient absorption in soybean plants (*Glycine max* L.) at the V3 and R1 growth stages was quantified using portable and benchtop X-ray fluorescence (pXRF) equipment to determine absorption dynamics over time. Additionally, synchrotron-based imaging was employed to analyze elemental distribution across the leaf surface following application. Powdery Mildew severity was assessed 15 days post-application to evaluate disease control efficacy.

Results Mn and Zn were more effectively absorbed when applied as sulfates and without mixture. However, when EDTA-chelated Mn and Zn were combined with emulsifiable concentrate fungicides, absorption rates surpassed those observed with fertilizers applied alone. Synchrotron analysis revealed complete diffusion of Mn and Zn throughout the treated leaf area within 48 h. Furthermore, fungicides were effective in disease control when applied both alone and in combination with foliar soluble fertilizers.

Conclusion Tank mix of soluble fertilizers and fungicides interferes with nutrient absorption, but under greenhouse conditions, no negative effects were observed on disease control efficacy.

Keywords Foliar fertilizers · Fungicides · X-ray fluorescence · Tank mix · Foliar absorption · Disease control

1 Introduction

High crop yields depend on several agronomical practices, including the proper supply of mineral nutrients and agrochemicals (Rodrigues et al. 2021; Caldwell et al. 2017). The combination of compounds, such as fungicides and fertilizers, into a single tank mix is a common practice in many crop species, including soybean

(*Glycine max* L.) (De Almeida Machado et al. 2020). This approach promotes precise delivery of these compounds while reducing the frequency of spraying by self-propelled vehicles or aircraft, hence minimizing the damage caused by terrestrial vehicles on soil, as well as reducing fuel consumption, water use, and operational time costs (Gazziero 2015).

Given the increasing complexity of agricultural formulations, including the reduction of spray volume, there is a rising demand for a proper understanding of tank mixtures, as their physical-chemical properties, such as surface tension, pH, electrical conductivity, and solution stability, can ultimately influence the effectiveness of plant treatments (Maciel et al. 2010; Petter et al. 2013). Mixtures may exhibit additive, synergistic, or antagonistic effects, i.e., where the combined compounds achieve either equal, increased, or reduced performances, impacting pest control and leading to possible toxicological risks (Ikeda 2013).

✉ Hudson Wallace Pereira de Carvalho
hudson@cena.usp.br; hudson.carvalho@um6p.ma

¹ Center for Nuclear Energy in Agriculture, University of São Paulo, Piracicaba, SP, Brazil

² Biology and Biotechnology Department “Charles Darwin”, Sapienza University of Rome, Rome, Italy

³ Global Critical Zone Science Chair, University Mohammed VI Polytechnic, Ben Guerir, Morocco

Manganese (Mn) and zinc (Zn) are essential micronutrients for plant metabolism. Mn acts as a cofactor in about 6% of plant metalloenzymes, supports reactive oxygen species detoxification, and plays a key role in photosynthesis via the oxygen-evolving complex of photosystem II (Kok et al. 1970; Schmidt et al. 2013). Zn, present in roughly 9% of the eukaryotic proteome, regulates nitrogen metabolism, activates enzymes and transcription factors like zinc-finger proteins, and protects cell membranes from oxidative damage (Stanton et al. 2022; Hafeez et al. 2013; Broadley et al. 2012; Kirkby and Römheld 2004). It also promotes leaf expansion and protein synthesis, which are quickly restored with Zn supplementation (Elsby 2008; Patel et al. 2007). Soil availability of both nutrients depends on factors like pH and oxygen levels, and deficiencies lead to chlorosis and stunted growth. In crops like soybean, Mn and Zn uptake ranges from 285 to 385 g ha⁻¹ and 310–432 g ha⁻¹, respectively, with significant portions exported through harvested grains (Bender et al. 2015).

To sustain nutrient availability for future crops, it is essential to maintain adequate levels of Zn and Mn in the soil, particularly in tropical and subtropical regions where soil type, pH, and climate significantly affect their availability to plants (Xia et al. 2024; Martins et al. 2008; Chiarini et al. 1998). For instance, in Brazil, optimal soybean development and high yields are expected at 5 and 1.3 mg dm⁻³ Mn and Zn soil concentration values (Cantarella et al. 2022). However, the available soil Mn and Zn contents are usually found at 5.47 and 0.83 mg dm⁻³, respectively (Verdame et al. 2007). Hence, 350 and 250 g ha⁻¹ Mn and Zn fertilization is often recommended to ensure adequate supply during the current and subsequent cropping seasons (Resende 2004). The fertilization timing, i.e., before the onset of the plant's reproductive (flowering) stage, is also critical to prevent Mn and Zn scarcity at key growth stages intricately tied with yield.

Foliar-based Mn and Zn delivery enables their rapid absorption and availability. Typical sources include oxides and carbonate concentrated suspensions, soluble, e.g., chlorides, sulfates, and nitrates, and complexes or chelates with ligands like EDTA, amino acids, citrate, and lignosulfonate. Although soluble salt sources (sulfates and chlorides) are usually cheaper, they are also highly reactive and potentially incompatible with other agrichemicals, while chelated sources, although costly, provide more stability in tank mixes (Alshaal and El-Ramady 2017).

Foliar-applied nutrients penetrate the leaf mainly through the cuticle and the stomata. Although the relative importance of each structure is still widely discussed (Eichert and Goldbach 2008), the penetration efficiency depends on the properties of the sprayed compound, such as its water

solubility and particle size, and the characteristics of the leaf surface, including wettability, cuticle composition, and stomatal density. Nutrient penetration into leaf surfaces occurs passively, driven by the concentration gradient between the surface and the leaf interior.

It is noteworthy to emphasize that, despite being widely employed, the “foliar uptake”, which implies the active absorption of the applied nutrients by the plants, is often misleading. It is crucial to distinguish the nutrient uptake into the leaf cells and their subsequent absorption and long-distance transport. Herein, we focused specifically on the initial penetration process termed foliar absorption in this paper.

Moreover, proper control of fungal diseases is crucial for the effective development of crop species. Powdery mildew (*Erysiphe diffusa*) can cause significant yield losses in soybean crops, leading to a drop in productivity of up to 50% during vegetative growth stages (Igarashi et al. 2020). The fungus infects plants by developing white-to-grey mycelial and conidial growth on aerial parts, starting with fine fungal layers on the upper leaf surfaces. As the infection progresses, it spreads extensively, disrupting essential physiological processes like photosynthesis and transpiration (Dunleavy 1978).

Systemic fungicides are particularly effective among the fungicides used for control. These compounds are absorbed by the plant, offering internal protection against fungal pathogens. Examples include triazoles, which inhibit ergosterol biosynthesis, and strobilurins, which interfere with mitochondrial respiration (Tleuova et al. 2020). However, little is known about their interaction when applied in conjunction with foliar fertilizers.

Therefore, this study hypothesizes that the mixtures of soluble fertilizers with fungicides reduce effectiveness and impair micronutrient absorption. The aim is to elucidate the effects of combining Mn and Zn soluble fertilizers (based on sulfate anion and EDTA chelate) with emulsifiable concentrate fungicide (difenoconazole and cyproconazole) and suspension concentrate fungicide (bixafen, trifloxystrobin, and prothioconazole) on the foliar absorption of Mn and Zn, as well as on the control of powdery mildew. Soybean was chosen as a model species because of its importance as a protein and oil source worldwide, and a crop frequently subjected to combined fertilizer and fungicide foliar applications. By examining these interactions in the context of foliar application, we seek to understand how fungicide treatments may influence the availability and absorption of these nutrients, and whether the mixture reduces disease control. Ultimately, we expect to contribute to more effective fertilization strategies for soybean plants.

2 Materials and methods

2.1 Reagents

The study employed the following sources of manganese (Mn) and zinc (Zn): $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ (31.85 wt% Mn, Synth, Brazil), $\text{ZnSO}_4 \cdot 7 \text{H}_2\text{O}$ (22.73 wt% Zn, Synth, Brazil), manganese ethylenediaminetetraacetate (Mn-EDTA) (13 wt% Mn, ICL, Brazil), and zinc ethylenediaminetetraacetate (Zn-EDTA) (15 wt% Zn, ICL, Brazil). Furthermore, two commercial fungicides: (i) suspension concentrate (SC) containing an active ingredient (AI) of 125 g L⁻¹ Bixafen, 175 g L⁻¹ of Prothioconazole, 150 g L⁻¹ of trifloxystrobin, and 730 g L⁻¹ other ingredients; (Bayer); (ii) emulsifiable concentrate (EC) consisting of active ingredient (AI) 250 g L⁻¹ of Difenconazole, 150 g L⁻¹ of Cyproconazole and 740 g L⁻¹ of other ingredients (Syngenta). The manufacturer did not disclose the details of the other ingredients in the emulsifiable and suspension concentrate fungicide formulations.

All formulations were prepared using 0.25% of an adjuvant consisting of fatty acid esters of plant origin, with 930 g L⁻¹ vegetal oil and 70 g L⁻¹ other ingredients. The manufacturer did not disclose the details of the other ingredients. These other ingredients generally include surfactants, diluents, or adjuvants, which stabilize the formulation and enhance the product's penetration into plants. However, the specific composition is classified as confidential commercial information (Defarge et al. 2018).

2.2 Solution and Suspension Preparation

The emulsifiable concentrate fungicide solution was prepared at a rate of 0.3 L ha⁻¹, while the suspension concentrate fungicide solution was prepared at 0.5 L ha⁻¹, following the manufacturer's instructions. Considering a spray mix volume of 70 L ha⁻¹, the final concentration for Mn and Zn was set at 4.28 g L⁻¹, equivalent to 300 g of Mn ha⁻¹ and 300 g of Zn ha⁻¹, and to the fungicides 4.28 and 7.14 mL L⁻¹ for emulsifiable concentrate and suspension concentrate, respectively.

The solutions were prepared following the guidelines from the Brazilian Agricultural Research Corporation (Gazziero et al. 2021). Briefly, 30 mL of water was agitated, then 112.5 µL of adjuvant was added, followed by the fungicide (321 µL for the concentrate suspension and 192.8 µL for the emulsifiable concentrate), and finally 15 mL of the $\text{Mn}_{0.54}\text{Zn}_{0.46}$ solution (from sulfate or EDTA chelate sources). The pH and electrical conductivity of the solution are listed in Table S2.

2.3 Plant Cultivation

2.3.1 Growing Vermiculite

Soybean seeds (cultivar M917IPRO) were sown in 2.5 dm³ pots containing 0.5 kg of expansive vermiculite (Natura in vita, Brazil). The plants were grown in a greenhouse under natural photoperiod and solar irradiance (without supplemental lighting) with 37 ± 5 °C and 20 ± 2 °C day and night temperatures, and 25 ± 5% to 78 ± 8% relative air humidity. The substrate was irrigated daily using a modified Cakmak's nutrient solution (as detailed in Table S1), and the moisture was kept at 70% water-holding capacity. The experimental setup consisted of plants grown at a density of three per pot. A total of 42 plants were utilized as follows: 30 plants for foliar absorption measurements and 15 plants for synchrotron-based imaging analysis.

2.3.2 Growing Soil

A full-cycle experiment was carried out under greenhouse under natural photoperiod and solar irradiance (without supplemental lighting), between November 2023 and January 2024 in the municipality of Piracicaba, Brazil (547 m altitude, 22°42'S, 47°38'W). In this regard, soybean seeds (cultivar, M917IPRO) were sown in 5 dm³ pots containing 5 kg of clay soil (5 seeds pot⁻¹). The average temperatures ranged from 37 ± 5 °C during the day to 20 ± 2 °C at night, while the relative humidity fluctuated between 20 and 30% minimum and 70–86% maximum values, respectively. The nitrosol soil (Nitossolo Vermelho Eutroférrido Latossólico – accord to Brazilian system) used to fill the pots was collected at the experimental area at the Luiz de Queiroz College of Agriculture of the University of São Paulo, in Piracicaba, Brazil, and subjected to chemical analyses, as shown in Table S1. Plants were grown at a density of two per pot with five replicates per treatment (90 plants total). Soil moisture was maintained at 70% water-holding capacity using deionized water. The plant population was equally divided between two evaluation groups: 45 plants for foliar absorption and 45 for disease control and grain yield assessments.

2.4 In Vivo Foliar Absorption Kinetics Assay

After reaching the V2 phenological stage, i.e., when two completely expanded trifoliate leaves were present, the plants in vermiculite were carefully transferred to the individual acrylic sample holders specifically developed for this analysis, as shown in Fig. S1. For each treatment, detailed in Table 1, using a micropipette (Eppendorf Research[®] plus),

Table 1 Composition of the tank mixtures employed. These combinations are aimed at mimicking spray tank mixtures commonly employed by farmers at a 70 L ha⁻¹ rate

Treatment	Composition	Concentration	Dose
Control	Deionized water	-	-
Sulfate	MnSO ₄ ·H ₂ O	Mn: 4.28 g L ⁻¹	300 g ha ⁻¹
	ZnSO ₄ ·7H ₂ O	Zn: 4.28 g L ⁻¹	300 g ha ⁻¹
EDTA	Mn-EDTA	Mn: 4.28 g L ⁻¹	300 g ha ⁻¹
	Zn-EDTA	Zn: 4.28 g L ⁻¹	300 g ha ⁻¹
Suspension Concentrate (SC)	Bixafen, Prothioconazole, Trifloxystrobin	7.14 mL L ⁻¹	0.5 L ha ⁻¹
Emulsifiable Concentrate (EC)	Difenoconazole, Cyproconazole	4.28 mL L ⁻¹	0.3 L ha ⁻¹
SC+Sulfate	Bixafen, Prothioconazole, Trifloxystrobin	7.14 mL L ⁻¹	0.5 L ha ⁻¹
	MnSO ₄ ·H ₂ O	Mn: 4.28 g L ⁻¹	300 g ha ⁻¹
	ZnSO ₄ ·7H ₂ O	Zn: 4.28 g L ⁻¹	300 g ha ⁻¹
EC+Sulfate	Difenoconazole, Cyproconazole	4.28 mL L ⁻¹	0.3 L ha ⁻¹
	MnSO ₄ ·H ₂ O	Mn: 4.28 g L ⁻¹	300 g ha ⁻¹
	ZnSO ₄ ·7H ₂ O	Zn: 4.28 g L ⁻¹	300 g ha ⁻¹
SC+EDTA	Bixafen, Prothioconazole, Trifloxystrobin	7.14 mL L ⁻¹	0.5 L ha ⁻¹
	Mn-EDTA	Mn: 4.28 g L ⁻¹	300 g ha ⁻¹
	Zn-EDTA	Zn: 4.28 g L ⁻¹	300 g ha ⁻¹
EC+EDTA	Difenoconazole, Cyproconazole	4.28 mL L ⁻¹	0.3 L ha ⁻¹
	Mn-EDTA	Mn: 4.28 g L ⁻¹	300 g ha ⁻¹
	Zn-EDTA	Zn: 4.28 g L ⁻¹	300 g ha ⁻¹

0.5 µL (containing 2.4 µg of Mn and 2.4 µg of Zn) droplets were applied in the adaxial face of the leaves. After drying, the exposed regions were evaluated through *in vivo* microprobe X-ray fluorescence spectroscopy (XRF) line-scanning at 1, 12, 24, 48, 72, and 96 h after application to assess the absorption kinetics of Mn and Zn fertilizers, either mixed or not with fungicides. The XRF analyses were carried out using benchtop equipment (Orbis PC, EDAX, USA) furnished with a 1 mm pinhole-collimated X-ray beam originating from a Rh anode operating at 45 kV and 900 µA, with a 25-µm-thick Al primary filter selected. Each point was evaluated for 15 s, and the spectra were recorded by a silicon drift detector (SDD) with a dead-time < 10%. The experiment was conducted using 5 independent biological replicates for each treatment. During the analysis, the plants were kept in a growth chamber with a 12-hour photoperiod, at 27° C ± 3° C, and relative humidity controlled at 80 ± 5%. The obtained Mn and Zn count rates were integrated and normalized to the values recorded in the first measurement

to assess their absorption as a function of time, according to the methodology described by Corrêa et al. (2021).

2.5 Assessment of elemental distribution on leaf tissues through synchrotron-based X-ray fluorescence spectroscopy imaging

The spatial distribution patterns of the absorbed nutrients within the leaves were traced using synchrotron-based X-ray fluorescence spectroscopy. A total of 15 plants at the V2 stage (*n* = 3 per treatment), grown under greenhouse conditions, were evaluated. Five representative treatments were selected: (i) control, (ii) Mn/Zn sulfate and (iii) Mn/Zn EDTA-chelate, both with and without (iv, v) SC fungicide, because of their kinetic stability in foliar absorption. For this, leaves of soybean plants were exposed to 0.5 µL droplets of the respective solutions, as these groups represented the key absorption patterns observed in the kinetic assays. After 48 h under high humidity conditions, the leaves were detached from the plants, and the treated regions were manually excised using a razor blade, embedded in optimal cutting temperature (OCT) medium (Tissue Plus, Fischer HealthCare, USA), and immediately plunged into liquid isopentane (Dinamica, Brazil) supercooled with liquid N₂. The cryofixed blocks were then kept at -25° C, fixed on an adhesive cellophane film (Fitar, Brazil), and cut using a cryostat (CM1850, Leica, Wetzlar, Germany) at -25° C. The resulting 30-µm-thick cross was immediately placed in the XRF sample holder sealed with a 6-µm-thick polypropylene (FPP25-R3, VHVG, USA) thin film and transferred to the beamline.

The XRF mapping of the sampled leaf cross-sections was performed at the Tarumã end station of the Carnaubá coherent X-ray nanoprobe beamline of the Brazilian Synchrotron Light Laboratory, in Campinas, Brazil. The beamline exhibits a horizontal deflection four-bounce crystal monochromator, two four-element silicon drift detectors (Vortex-ME4, Hitachi High-Technologies Science America, USA), and a Kirkpatrick-Baez (KB) achromatic optic providing a ca. 150 nm-wide X-ray focused beam spot. The XRF maps were recorded in the flyscan mode at an energy slightly higher than the Zn K edge-line excitation energy (10300 eV) through 250 × 250 µm panoramic images with a 5 µm lateral resolution. The measurements were performed at room temperature. The data were processed using the PyMca software (version 5.6.3, ESRF Software Group, France). The ring current normalized elemental intensities found at each pixel unit and fitted according to the beamline instrumental parameters. The analyses were carried out using 3 independent replicates for each condition.

2.6 Evaluation of Mn and Zn Foliar Absorption in Greenhouse Conditions

During the R1 stage, treatments (Table 1) were applied via foliar spray using a manual pressure sprayer with a fine mist nozzle, at 280 μL per plant (containing 1.19 mg of Mn and 1.19 mg of Zn) and performed overhead (from top to bottom), targeting the upper canopy to simulate standard field-scale foliar spraying conditions. This value was chosen based on the premise of a volume of the tank of 70 L ha^{-1} and a plant population of 250,000 plants ha^{-1} . In addition, plants were arranged in a completely randomized design.

After 7 days, the last 5 fully developed trifoliates that received the spray were collected to determine the content of Mn and Zn absorbed by the leaves. The collected leaves were submitted to a washing sequence determined by Embrapa (2009), which begins with washing in running water and deionized water, followed by washing in a detergent solution (1%) and then again in deionized water. Finally, they are immersed in a hydrochloric acid solution (3%) for 1 min and finished with another wash in deionized water. They were then dried in a forced circulation drying oven (FANEM, model 320/4, Brazil) for 48 h and finally ground into a homogenized fine powder using an electric grinder (Cadence, model MDR302-127, China) and passed through a 100-mesh sieve ($<150 \mu\text{m}$) to ensure analytical uniformity.

One hundred milligrams of the ground samples were added to X-ray sample cups (Spex Sample Prep, no. 3577, USA), sealed with 6- μm -thick polypropylene film, and manually pressed using a glass rod (Montanha et al. 2024). The samples were analyzed by an X-ray fluorescence spectrometer (Bruker Tracer Vision III-SD, USA) using a Rh X-ray tube at 40 kV and 30 μA , and a primary filter of 304.8 μm Al+25.4 μm Ti. The X-ray spectra was recorded during 120 s by a silicon drift detector (SDD). The analysis was carried out under an air pressure atmosphere. The quantification was performed using the standard addition method, in which 20, 50, 100, 150, 300, and 1000 mg kg^{-1} of Mn and

Zn (from 1,000 to 10,000 mg L^{-1} Mn and Zn stock solution, Specscol, Brazil) were added to 0.500 g of a ground soybean leave sample. The X-ray sample spectra were processed using Spectra Artax software (Version 7.4.0.0). The Mn and Zn K α net intensities were normalized by Rh K α Compton scattering for the quantification analysis.

2.7 Effect of Tank Mix on Disease Control and Plant Grain Yield

To evaluate the effectiveness of the fungicides as a function of the association with Mn and Zn fertilizers, the central leaflets of the third fully expanded trifoliolate were photographed 15 days after the spraying. The frequency of lesions was observed the severity of the disease was determined according to Godoy et al. (2006) diagrammatic 2-scale, as shown in Fig. 1.

Moreover, at the maturity stage, the pods were collected, and the detached grains were dried at 60 $^{\circ}\text{C}$ in a forced circulation drying oven (FANEM LTDA model 320/4) for 48 h. The plant yield was measured in grams of grain per plant, according to Perini et al. (2012).

2.8 Statistical Analysis

All quantitative data were subjected to one-way analysis of variance (ANOVA) followed by Tukey's post hoc test at a 95% confidence interval. The normality of the data was evaluated through the Shapiro-Wilk test at a significance level of 0.05. All data were processed using OriginLab (v. 2022b, Northampton, MA, USA).

3 Results

3.1 Foliar Absorption of Nutrients

Figure 2, representing plants at the V2 stage, illustrates the absorption rates of leaves exposed to sulfate and

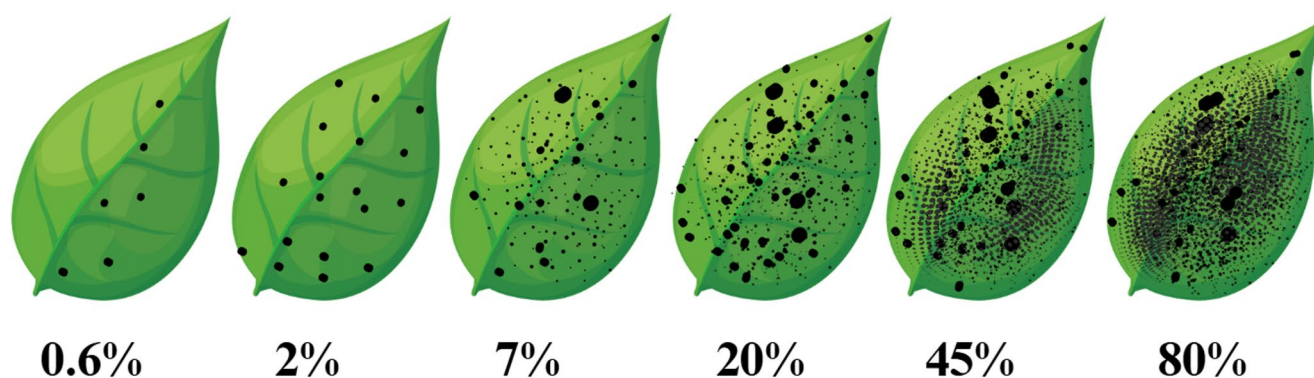


Fig. 1 Diagram inspired by the scale used to determine the severity of foliar diseases

EDTA-chelated Mn and Zn solutions, both with and without fungicides, over 96 h. The data reveal a significant decrease in Mn absorption from sulfate when fungicides are applied (Fig. 2A). Specifically, absorption dropped to zero after 12 h with an EC fungicide, while the SC fungicide showed an initial increase followed by an exponential rise, ultimately yielding total absorptions of 70%, 50%, and 25% for $\text{Mn}(\text{SO}_4)$, $\text{EC} + \text{Mn}(\text{SO}_4)$, and $\text{SC} + \text{Mn}(\text{SO}_4)$, respectively.

For $\text{Mn}[\text{EDTA}]$, the presence of fungicides enhanced absorption rates (Fig. 2C), with total absorptions of 63%, 55%, and 42% for the mixtures $\text{EC} + \text{Mn}[\text{EDTA}]$, $\text{SC} + \text{Mn}[\text{EDTA}]$, and $\text{Mn}[\text{EDTA}]$, respectively. This demonstrates that combining $\text{Mn}[\text{EDTA}]$ with fungicides significantly improves absorption.

$\text{Zn}(\text{SO}_4)$ alone showed the highest absorption, while the order was $\text{Zn}(\text{SO}_4) > \text{emulsifiable concentrate} + \text{Zn}(\text{SO}_4) > \text{suspension concentrate} + \text{Zn}(\text{SO}_4)$ (Fig. 2B). Total absorptions were 42%, 33%, and 18%, respectively. In contrast, $\text{Zn}[\text{EDTA}]$ was better absorbed in a mixture with EC and

SC, achieving 54% absorption compared to just 34% when applied alone.

Figure 3, representing plants at the R1 stage, shows the concentration of Mn and Zn in the leaves sprayed with Mn and Zn nutrient sources alone or their mixtures with fungicides. It is worth mentioning that all leaves were washed to remove any residual Zn and Mn from the surface. The leaves from the control group plants presented an average of 37 and 56 mg kg^{-1} of Mn and Zn, respectively, whereas those exposed to the EC and SC fungicides exhibited 38 and 47 mg kg^{-1} for Mn and 56 and 53 mg kg^{-1} for Zn, respectively, highlighting that the foliar application of fungicides did not affect Zn and Mn concentrations in the leaves.

In addition, these results also showed that, under greenhouse conditions, both fungicides influenced the absorption of Mn and Zn by the leaves. For the manganese treatment without fungicide, the sulfate source had the highest concentration, i.e., 616 mg kg^{-1} , while the EDTA source alone had the lowest concentration, 203 mg kg^{-1} . However, when

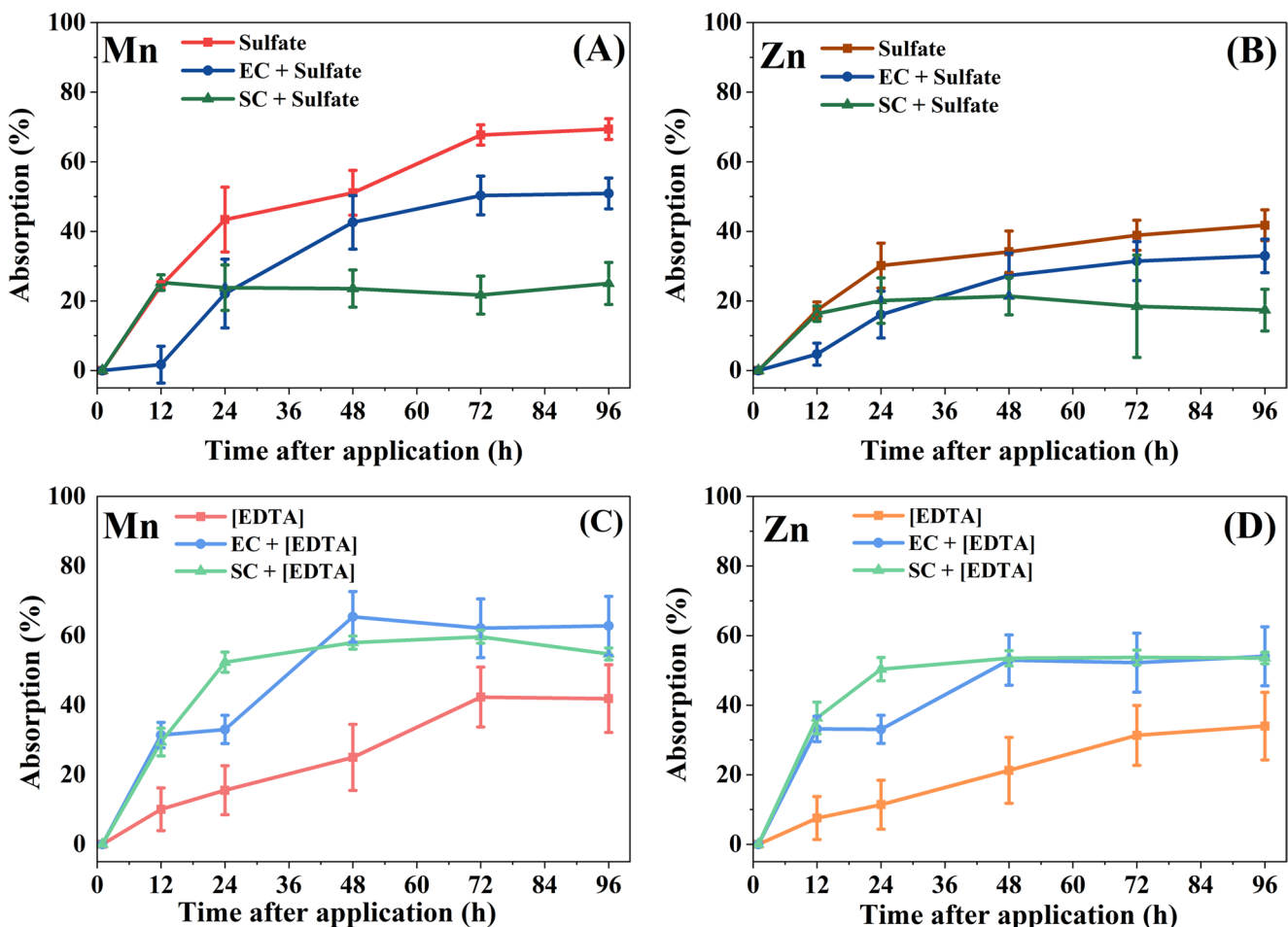


Fig. 2 Mn and Zn absorption in V2-stage soybean plants. (A and C) Absorption (%) of Mn fertilizers combined with or without EC and SC fungicides; (B and D) Absorption (%) of Zn fertilizers combined

with or without EC and SC fungicides. The bar illustrated in the figure representing the mean $\pm$ standard error from 5 biological replicates

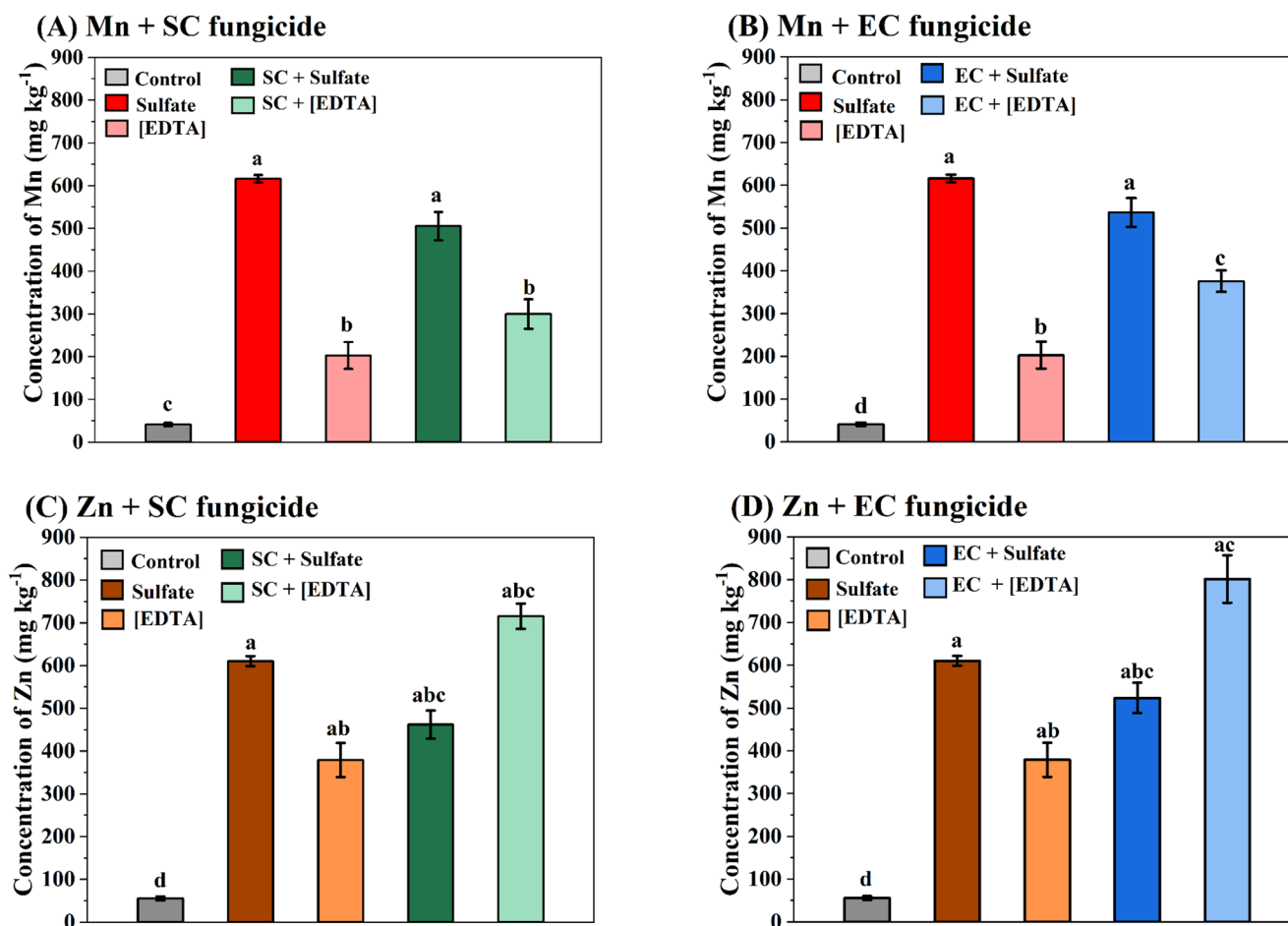


Fig. 3 Mn and Zn absorption in R1-stage soybean plants. (A and B) Concentration of Mn fertilizers combined with and without EC and SC fungicide in the leaves; (C and D) Concentration of Zn fertilizers combined with and without EC and SC fungicide in the leaves. The bar

illustrated in the figure represents the mean $\pm$ standard error from 5 biological replicates and different letters indicate statistically significant differences ($p < 0.05$) between treatments

both Mn sources were combined with fungicide, an opposite trend was observed; the Mn concentration decreased for the sulfate source and increased for the EDTA source. The highest concentration was observed for Zn treatments when EDTA was applied with fungicide, followed by Zn sulfate alone, zinc sulfate with fungicide, and finally EDTA alone. This concentration pattern remained consistent across both the EC and SC fungicide treatments (Fig. 3B and D).

Because EC and SC fungicides have equivalent interaction pattern in the absorption of Mn and Zn, only the EC fungicide was selected to understand whether the mixture would influence elemental redistribution within the leaves.

Figure 4A presents synchrotron-based XRF maps of RGB images, showing the spatial distribution of calcium (Ca), manganese (Mn), and zinc (Zn) in cross-sections of soybean leaves. It also contrasts the intensities within or around the cells in specific areas (Fig. 4BC), comparing leaves treated with EC to those untreated. The XRF maps

reveal that Mn and Zn signals were nearly absent in the epidermis, regardless of the foliar treatment. However, distinct distribution patterns emerged, with Zn and Mn missing in the epidermis for both EDTA and sulfate treatments, indicating different short-distance transport behaviors. The images further illustrate that the elements were effectively absorbed and localized in specific cellular compartments, indicating successful absorption and movement within the plant.

Figure 4C offers a detailed comparison of the intensity and distribution of Mn and Zn when applied as sulfate salt and EDTA chelate sources, combined with EC fungicide. Figure 3B shows the spatial distribution of Ca, which is used to differentiate and select regions inside and outside the cell, allowing for the evaluation of Zn and Mn intensity with and without the mixture. Figure 4C displays the intensities of Ca, Mn, and Zn in the selected region. The Mn and Zn concentrations in leaf tissue did not show significant

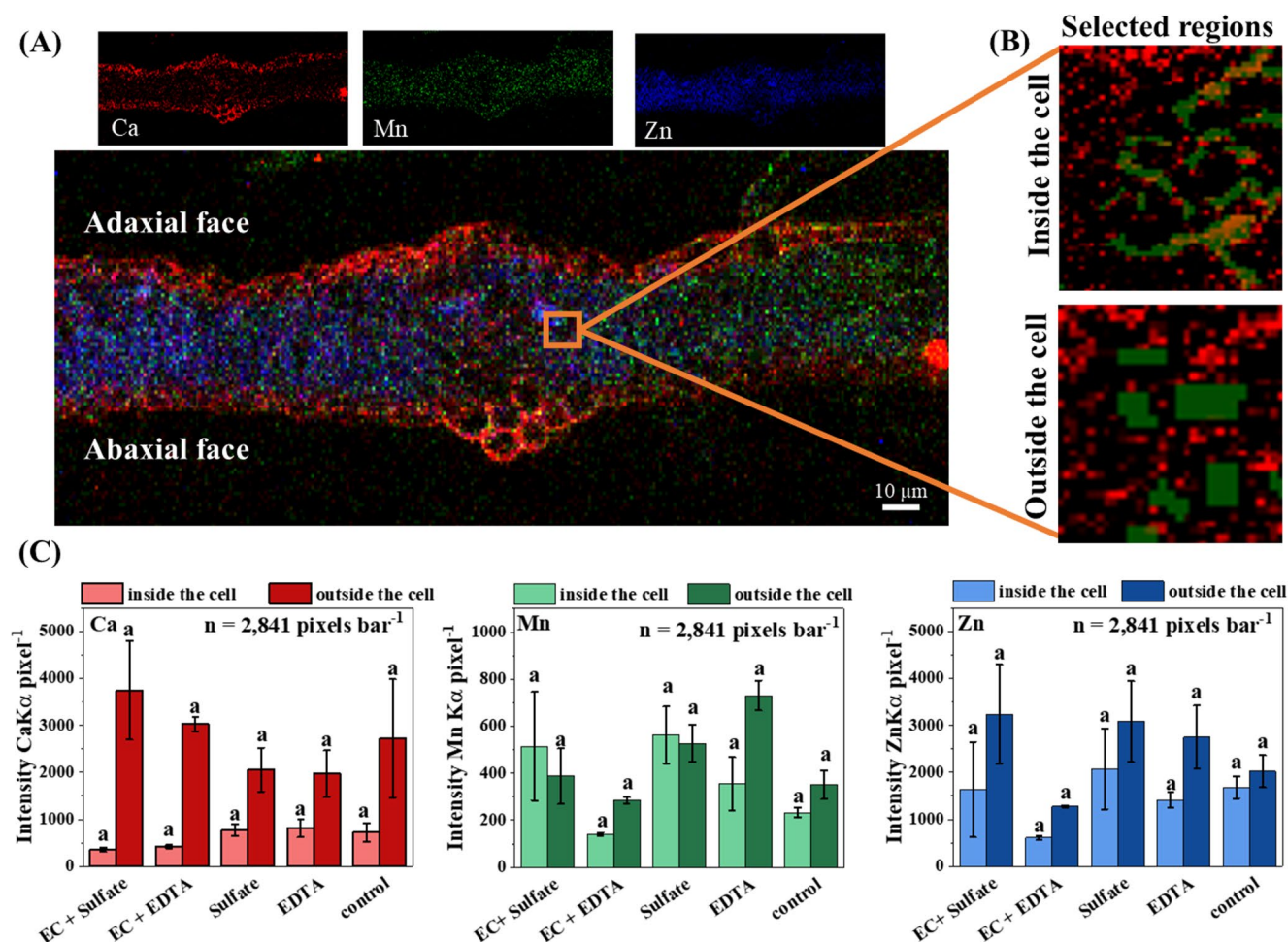


Fig. 4 Mn and Zn absorption in V2-stage soybean plants. (A) Images of 250×250 µm from the cross-section leaves after 48 h of application; (B) Regions marked to identify inside and outside cells in leaves; (C) Intensity of CaKα, MnKα, and ZnKα from the regions identified

as inside and outside cells. Data represents the mean±standard error from 3 biological replicates, and different letters indicate statistically significant differences both between cellular regions and across experimental treatments

differences between treatments, indicating that initial absorption, in V2 stage, was not affected by the source (sulfate or EDTA) or by the addition of EC fungicide. The cellular distribution of Mn and Zn remained balanced across most treatments, with higher intensity averages observed in the extracellular region. However, Mn from sulfate sources, applied with or without fungicides, did not follow this pattern. In contrast, the combination of EDTA chelate source with EC resulted in reduced intensity, suggesting rapid redistribution after 48 h.

3.2 Effect of Tank Mix on Disease Control

Table 2 presents the effectiveness of the fungicides, either combined or not with the fertilizers, on powdery mildew disease control on the sprayed leaves (detailed in Figure S4), and reveals that fungicide applications, both alone and

Table 2 Severity of disease before treatment, spraying, and disease control past 15 days of the application of treatments. Values represent the means±standard error, and different letters indicate statistically significant differences between treatments

Treatments	Severity before spraying of treatment (%)	Percentage of Disease Control (%)
Control	5±2.8 a	0
Sulfate	7±3.1 a	0
[EDTA]	6±1.8 a	0
EC	4±3.4 a	100
SC	4±3.6 a	100
SC+ Sulfate	7±2.4 a	100
SC+ [EDTA]	13±3.6 b	100
EC+ Sulfate	15±5.5 b	100
EC+ [EDTA]	11±2.4 b	100

in tank mixes with soluble fertilizers, were fully effective in controlling Powdery Mildew.

3.3 Effect of Tank Mix on Crop Yield

After the treatments were applied, the plants were grown until the senescence phase to evaluate productivity outcomes. As shown in Table 3, there were no statistically significant differences between the treatment groups. However, slight reductions in productivity were observed with certain mixed applications. For instance, the combined application of fungicides with $Mn_{0.54}Zn_{0.46}[EDTA]$ led to a 13% decrease in productivity compared to the untreated control group, which received neither fungicides nor fertilizers. Larger reductions, reaching 20%, were noted when this mixed treatment was compared to the isolated application of $Mn_{0.54}Zn_{0.46}(SO_4)$ and suspension concentrate.

4 Discussion

Although foliar absorption data indicate that Mn and Zn sulfate sources perform better than all other treatments, greenhouse results show that the mixture of Mn and Zn chelated with EDTA, combined with SC fungicide, led to greater accumulation of these nutrients in the leaves. This accumulation, however, can be attributed to reduced remobilization to other parts of the plant. This is evident in synchrotron imaging, which shows that after 48 h, the elemental distribution remains uniform within the treated spot. In contrast, sulfate-based sources promote remobilization of Mn and Zn within 24 h of application, which explains the lower leaf concentration in greenhouse conditions (Gomes et al. 2019; Rezende et al. 2025).

Our results revealed that combining Mn and Zn sulfate-based sources with both EC and SC fungicides resulted in a lower absorption rate of these nutrients. Such an effect might be attributed to interactions between Mn^{2+} and Zn^{2+} ions and the fungicide's active ingredient particles, compounds of organic molecules. However, one should also keep in mind that other factors, e.g., the physicochemical properties of the spray solution - solubility, electric charge, pH, surface

tension, and deliquescence point - can also affect the efficiency of nutrient absorption through the leaves (Fernández and Eichert 2009; Fernández and Brown 2013).

For instance, changes in the solution's pH have been reported to influence the absorption patterns of trifloxysulfuron by cotton plants (Matocha et al. 2006), where changing the pH of the solution from 5 to 9 resulted in a significantly increased absorption (from 52 to 60%, respectively). Changes in pH can occur when other components are added to the fungicide solution, which can lead to degradation of the fungicide and changes in the way plants absorb the fungicide. Herein, the pH variation was also observed after the tank mix of soluble fertilizers with fungicides (Table S3), but this variation did not interfere with the disease control of mildew.

A previous study showed an increase of 47% in cuticular penetration when Chlorantraniliprole was combined with Mn-sulfate, and an added organosilicon adjuvant in the mixture, penetration increased to 61%. In comparison, Mn-sulfate combined with an organosilicon adjuvant alone resulted in only 20% penetration, while Mn penetration without additives was as low as 3% (Zandonadi et al. 2018). These figures highlight that defensives can enhance Mn penetration more effectively than Mn-sulfate combined with adjuvants. In our research, the improved absorption, in tank mix, was observed from $Mn_{0.54}Zn_{0.46}[EDTA]$ in combination with fungicides EC and SC. This effect suggests that the interaction between the chelate agent and the active ingredients or the other ingredients used in the composition of the fungicides facilitates the foliar absorption in leaves.

Another factor potentially enhancing of Mn and Zn EDTA chelate source combined with fungicides is the positive interaction of other ingredients added that can interact with the cuticle, thus facilitating the chelated mineral. Although the specific details of the manufacturing process were not disclosed, these formulations generally include surfactants, diluents, or adjuvants, which stabilize the product and improve its penetration into the plants (Defarge et al. 2018). This interaction can be observed in iodine biofortification, six non-ionic surfactants, and oil-based adjuvants showed that the organosilicon-based adjuvant Pulse[®] significantly increased iodine concentration in grains ($1269 \mu g kg^{-1}$) compared to KIO_3 alone ($231 \mu g kg^{-1}$). Synerterol[®] Horti Oil also raised iodine levels ($450 \mu g kg^{-1}$), while other adjuvants had no significant effect (Magor et al. 2023). Similarly, in the use of chlorantraniliprole, where the concentration of $20 g ha^{-1}$ and mixed with a commercial adjuvant Natur'l Oil[®] formulation (soybean oil 93%) at a 0.5% concentration, resulting in the improved penetration of active ingredients of $10 mg kg^{-1}$ to $29 mg kg^{-1}$ in leaves of wheat (Melo et al. 2015). Another example was observed in the evaluation of plant oil, mineral oil, and a mix of alcohol

Table 3 Average grain yield expressed as $g plant^{-1}$. Values represent the means $\pm$ standard error, and different letters indicate statistically significant differences between treatments

Treatment	Seed yield ($g plant^{-1}$)
Control	4.8 ± 0.3 a
Sulfate	5.0 ± 0.6 a
[EDTA]	4.6 ± 0.1 a
EC	4.7 ± 1.1 a
SC	5.0 ± 0.7 a
SC+ Sulfate	4.6 ± 0.2 a
SC+ [EDTA]	4.2 ± 0.8 a
EC+ Sulfate	4.5 ± 0.3 a
EC+ [EDTA]	4.2 ± 0.5 a

and ester adjuvants in a mixture with nanopesticides, emulsifiable concentrate, and emulsion in water, where the use of mineral oil adjuvant improved the capacity for wetness for increased drop size, penetration, as well as improved the efficiency of pesticides (Hu et al. 2024).

When comparing EC and SC fungicides, a significant difference in absolute nutrient absorption is noticed, which can be attributed to the distinct formulations of each fungicide. EC fungicides are typically manufactured to yield higher dispersion and finer droplet formation, with particle sizes of 0.1–10 μm , facilitating both absorption and nutrient delivery (Brar et al. 2006). In contrast, SC fungicides contain larger particle sizes, ranging from 1 to 10 μm , which can hinder the solution's ability to penetrate the leaf, potentially limiting foliar absorption (Woods 2003). This difference in particle size and formulation may affect nutrient delivery effectiveness, influencing the concentration of Mn and Zn adsorbed on different particles and the potential for filter clogging due to particle aggregation of fungicides. When observing the absorption of zinc oxide (ZnO) suspensions, Gomes et al. (2019) found lower absorption rates of ZnO compared to zinc sulfate (ZnSO_4), a difference attributed to the larger particle size of the ZnO suspension. In the case of SC fungicide, the reduced absorption efficiency may be explained by a similar mechanism, where the larger particle size curbs the effective movement of nutrients across the leaf surface and into plant tissues.

While studying the penetration of ZnSO_4 in apple leaves, Xie et al. (2020) observed that trichomes on the leaf surface increased hydrophobicity, which hindered Zn absorption, while stomata facilitated Zn penetration. Furthermore, low Zn levels promoted the accumulation of other minerals in the leaves, while high Zn levels may have led to its complexation with phytic acid. These findings are critical for optimizing Zn biofortification strategies in crop species by considering leaf surface characteristics and Zn application rates. Our leaf cross-section maps show that, in addition to being absorbed, nutrients are transported through both the apoplastic and symplastic regions, thereby enabling redistribution to other parts of the leaf and plant, according to the mobility of each nutrient (Benitez-Afonso 2014).

On the other hand, mixing imidacloprid (initial pH 6.32, conductivity 4 $\mu\text{S cm}^{-1}$) with manganese sulfate reduced the pH to 4.55 and increased the electrical conductivity to 1729 $\mu\text{S cm}^{-1}$. This variation impacted psyllid (*Trioza limbate*) control, where imidacloprid alone reduced insect infestation by 20% after 7 days and 70% after 14 days. In a mixture with manganese sulfate, the infestation showed an increase of 27% in infestation after 7 days and a decrease of 54% after 14 days, indicating a retarded effect in controlling the psyllid infestation (Zandonadi et al. 2019). Different from what was reported above, the present study found

that the tank mix of soluble fertilizers with fungicides did not reduce the efficiency of disease control at low disease pressure.

The positive effective control of disease observed in this study, from the tank mix of soluble fertilizers of $\text{Mn}_{0.54}\text{Zn}_{0.46}$ with emulsifiable concentrate and suspension concentrate fungicides, contrasts with what was observed by Bernads et al. (2005) while studying herbicides. Evaluating the effect of Mn, Fe, Cu, and Zn nutrients from sulfate, citrate, and EDTA chelate sources in a mixture with glyphosate and commercial adjuvants CANG and NT observed antagonism in the efficiency absorption and translocation of glyphosate with decreases of up to 99% to Zn-sulphate (0.6 kg ha^{-1}) + adjuvant CANG (2.5% v/v) + glyphosate (0.28 kg ha^{-1}). Despite this large reduction, the biggest interferent proved to be the adjuvant CANG, because the same situation with variation to adjuvant NT, had interference, but the control was 54%. In this way, as well as the interference of nutrients, adjuvants can potentiate the antagonism of the pesticide.

Furthermore, a study using six different plant extracts to control late blight disease in tomato plants assessed the effectiveness of this control of *A. indica* in both greenhouse and field conditions. Using concentrations of 1% and 5% in the greenhouse resulted in reductions of 48.6% and 55%, respectively, in disease severity. In the field, only the 5% concentration led to a 35% reduction in disease severity. These data indicate that smaller doses in greenhouse conditions can be effective, or even more so, than higher concentrations in the field (Sallam 2011). The findings reported above reveal that the disease control obtained in the present study cannot necessarily be extrapolated to field conditions, i.e. even though the reaction between $\text{Mn}(\text{SO}_4)$ and $\text{Zn}(\text{SO}_4)$ with the fungicides did not impact the disease control in the greenhouse, it does not mean that the same will happen under field conditions because the rate of fungicide in those environments may change.

5 Conclusion

In conclusion, the absorption of Mn and Zn was compromised when added in the tank mix from the sulfate source, with both EC and SC fungicides being more expressive for SC, with reductions of 45%. On the other hand, the absorption of $\text{Mn}_{0.54}\text{Zn}_{0.46}$ from the EDTA chelate source proved to be less efficient compared to the mix with both fungicides, showing an increase in absorption compared to application alone, 21%. Using fungicides in a tank mix with soluble fertilizers did not affect disease control or interfere with grain yield under the conditions tested. However, further field evaluations are still required to ensure that the effectiveness of disease control or grain yield will not be compromised in

future applications based solely on the assumptions of this study. These findings suggest that the variations in pH and electrical conductivity, in mix, indicate the presence of reactions that influence the absorption efficiency of nutrients.

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Data Availability The data presented in this study are available upon request.

Code Availability Not applicable.

Declarations

Consent for Publication All authors agree to publish.

Ethics approval Not applicable.

Conflict of interest The authors declared that there is no conflict of interest.

Supporting Information Sample holder for evaluation of μ -XRF benchtop equipment., concentration used in the nutrient solution, physical and chemical results of soil used in the experiment, scale used to determine the severity of foliar diseases, pH and electrical conductivity of solutions used in application, calibration curve of manganese and zinc to quantify in the soybean leaves, replicate of synchrotron image and leaves before and after disease control.

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References

- Alshaal T, El-Ramady H (2017) Foliar application: from plant nutrition to biofortification. *Environ Biodivers Soil Secur* 1:71–83. <https://doi.org/10.21608/jenvbs.2017.1089.1006>
- Bender RR, Haegerle JW, Below FE (2015) Nutrient uptake, partitioning, and remobilization in modern soybean varieties. *Agron J* 107:563–573. <https://doi.org/10.2134/agronj14.0435>
- Benitez-Alfonso Y (2014) Symplastic intercellular transport from a developmental perspective. *J Exp Bot* 65:1857–1863. <https://doi.org/10.1093/jxb/eru067>
- Brar SK et al (2006) Recent advances in downstream processing and formulations of *Bacillus thuringiensis*-based biopesticides. *Process Biochem* 41:323–342. <https://doi.org/10.1016/j.procbio.2005.07.015>
- Broadley M et al (2012) Function of nutrients: micronutrients. Marschner's mineral nutrition of higher plants. Academic, New York, pp 191–248. <https://doi.org/10.1016/B978-0-12-384905-2.00007-8>
- Caldwell CD et al (2017) Effect of fungicide combinations for Fusarium head blight control on disease incidence, grain yield, and quality of winter wheat, spring wheat, and barley. *Can J Plant Sci* 97:1036–1045. <https://doi.org/10.1139/cjps-2017-0001>
- Cantarella H et al (2022) Recomendações de adubação e calagem para o estado de São Paulo. Instituto Agrônomo de Campinas, Campinas. DOI: <https://www.iac.sp.gov.br/publicacoes/boletim100.php>
- Chiarini L et al (1998) Influence of plant development, cultivar and soil type on microbial colonization of maize roots. *Appl Soil Ecol* 8:11–18. [https://doi.org/10.1016/S0929-1393\(97\)00071-1](https://doi.org/10.1016/S0929-1393(97)00071-1)
- Corrêa CG et al (2021) Effect of counterions on the foliar absorption and transport of potassium in soybeans [*Glycine max* (L.) Merril]. *ACS Agric Sci Technol* 1:728–734. <https://doi.org/10.1021/acsagsscitech.1c00211>
- De Almeida Machado B et al (2020) Understanding the chemistry of manganese fertilizers and glyphosate mixtures by using synchrotron X-ray spectrometry. *SN Appl Sci* 2:1837. <https://doi.org/10.1007/s42452-020-03632-y>
- Defarge N, De Vendômois JS, Séralini GE (2018) Toxicity of formulations and heavy metals in glyphosate-based herbicides and other pesticides. *Toxicol Rep* 5:156–163. <https://doi.org/10.1016/j.toxrep.2017.12.025>
- De Resende AV (2004) Adubação da soja em áreas de cerrado: micronutrientes. DOI: <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/569152>
- Dunleavy JM (1978) Soybean seed yield losses caused by powdery mildew 1. *Crop Sci* 18:337–339. <https://doi.org/10.2135/cropsci1978.0011183x001800020037x>
- Eichert T, Goldbach HE (2008) Equivalent pore radii of hydrophilic foliar uptake routes in stomatous and astomatous leaf surfaces—further evidence for a stomatal pathway. *Physiol Plant* 132:491–502. <https://doi.org/10.1111/j.1399-3054.2007.01023.x>
- Elsby LM, Roberts SGE (2008) Interaction of the TFIIB zinc ribbon with RNA polymerase II. *Biochem Soc Trans* 36:595–598. <https://doi.org/10.1042/BST0360595>
- Fernández V, Brown PH (2013) From plant surface to plant metabolism: the uncertain fate of foliar-applied nutrients. *Front Plant Sci* 4:289. <https://doi.org/10.3389/fpls.2013.00289>
- Fernández V, Eichert T (2009) Uptake of hydrophilic solutes through plant leaves: current state of knowledge and perspectives of foliar fertilization. *Crit Rev Plant Sci* 28:36–68. <https://doi.org/10.1080/07352680902743069>
- Gazziero DLP (2015) Mixtures of pesticides in tank, in Brazilian farms. *Planta Daninha* 33:83–92. <https://doi.org/10.1590/S0100-83582015000100010>

- Gazziero DLP et al (2021) Manual técnico para subsidiar a mistura em tanque de agrotóxicos e afins. Embrapa Soja, Londrina. DOI: <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1132371>
- Godoy CV, Koga LJ, Canteri MG (2006) Diagrammatic scale for assessment of soybean rust severity. Fitopatol Bras 31:63–68. <https://doi.org/10.1590/S0100-41582006000100011>
- Gomes MHF et al (2019) In vivo evaluation of Zn foliar uptake and transport in soybean using X-ray absorption and fluorescence spectroscopy. J Agric Food Chem 67:12172–12181. <https://doi.org/10.9734/AJEA/2013/2460>
- Hafeez BMKY, Khanif YM, Saleem M (2013) Role of zinc in plant nutrition: a review. Am J Exp Agric 3:374–391. <https://doi.org/10.9734/AJEA/2013/2746>
- Hu H et al (2024) Tank-mix adjuvants enhance pesticide efficacy by improving physicochemical properties and spraying characteristics for application to cotton with unmanned aerial vehicles. ACS Omega 9:31011–31025. <https://doi.org/10.1021/acsomega.4c04301>
- Igarashi S et al (2020) Danos causados pela infecção de oídio em diferentes estádios fenológicos da soja. Arq Inst Biol 77:245–250. <https://doi.org/10.1590/1808-1657v77p2452010>
- Ikeda FS (2013) Weed resistance in glyphosate-resistant soybean. Inf Agropecu 34:276. <https://doi.org/10.5555/20133424194>
- Kirkby EA, Römhild V (2004) Micronutrients in plant physiology: functions, uptake and mobility. In: Proceedings of the International Fertiliser Society 543. International Fertiliser Society, York, pp 1–52. <https://doi.org/10.1016/B978-0-85310-179-6.50006-4>
- Kok B, Forbush B, McGloin M (1970) Cooperation of charges in photosynthetic O₂ evolution – I. A linear four-step mechanism. Photochem Photobiol 11:457–475. <https://doi.org/10.1111/j.1751-1097.1970.tb06017.x>
- Maciel CDG et al (2010) Static surface tension of glyphosate + chlorimuron-ethyl tank mixtures, alone or with adjuvants. Planta Daninha 28:673–675. <https://doi.org/10.1590/S0100-8358201000300025>
- Magor E et al (2023) Selected adjuvants increase the efficacy of foliar biofortification of iodine in bread wheat (*Triticum aestivum* L.) grain. Front Plant Sci 14:1246945. <https://doi.org/10.3389/fpls.2023.1246945>
- Martins FB et al (2008) Deficiência hídrica no solo e seu efeito sobre transpiração, crescimento e desenvolvimento de mudas de duas espécies de eucalipto. Rev Bras Ciênc Solo 32:1297–1306. <https://doi.org/10.1590/S0100-06832008000300037>
- Matocha MA et al (2006) Spray carrier pH effect on absorption and translocation of trifloxysulfuron in Palmer amaranth (*Amaranthus palmeri*) and Texasweed (*Caperonia palustris*). Weed Sci 54:969–973. <https://doi.org/10.1614/WS-06-029.1>
- Melo AA et al (2015) Impact of tank-mix adjuvants on deposit formation, cuticular penetration, and rain-induced removal of chlorantraniliprole. Crop Prot 78:253–262. <https://doi.org/10.1016/j.cropro.2015.09.021>
- Montanha GS et al (2024) Profile of mineral nutrients and proteins in soybean seeds (*Glycine max* (L.) Merrill): Insights from 95 varieties cultivated in Brazil. J Food Compos Anal 134:106536. <https://doi.org/10.1016/j.jfca.2024.106536>
- Patel K, Kumar A, Durani S (2007) Analysis of the structural consensus of the zinc coordination centers of metalloprotein structures. Biochim Biophys Acta Proteins Proteom 1774:1247–1253. <https://doi.org/10.1016/j.bbapap.2007.07.010>
- Perini et al (2012) Components of the production in soybean cultivars with determinate and indeterminate growth. Semina Ciênc Agrár 33:2531–2544. <https://doi.org/10.5433/1679-0359.2012v33n6Supl1p2531>
- Petter FA et al (2013) Physical incompatibility of insecticide and fungicide mixtures. Comunicata Sci 4:129–138. <https://doi.org/10.14295/cs.v4i2.152>
- Rezende VP et al (2025) Foliar absorption and translocation of metal-amino acid complexes in soybean: A case study of manganese, zinc, glutamate, and histidine. ACS Agric Sci Technol. <https://doi.org/10.1021/acsaagritech.5c00364>
- Rodrigues VA et al (2021) Magnesium foliar supplementation increases grain yield of soybean and maize by improving photosynthetic carbon metabolism and antioxidant metabolism. Plants 10:797. <https://doi.org/10.3390/plants10040797>
- Sallam NMA (2011) Control of tomato early blight disease by certain aqueous plant extracts. Plant Pathol J 10:168–174. <https://doi.org/10.3923/ppj.2011.187.191>
- Schmidt SB et al (2013) Latent manganese deficiency in barley can be diagnosed and remediated on the basis of chlorophyll a fluorescence measurement. Plant Soil 372:417–429. <https://doi.org/10.1007/s11104-013-1702-4>
- Stanton C et al (2022) Zinc in plants: Integrating homeostasis and biofortification. Mol Plant 15:65–85. <https://doi.org/10.1016/j.molp.2021.12.008>
- Tleuova AB et al (2020) Recent advances and remaining barriers to producing novel formulations of fungicides for safe and sustainable agriculture. J Control Release 326:468–481. <https://doi.org/10.1016/j.jconrel.2020.07.035>
- Vendrame PRS et al (2007) Disponibilidade de cobre, ferro, manganês e zinco em solos sob pastagens na região do Cerrado. Pesq Agropec Bras 42:859–864. <https://doi.org/10.1590/S0100-204X2007006000013>
- Woods TS (2003) Pesticide formulations. Encyclopedia of Agrochemicals. John Wiley & Sons, Inc., New York. DOI: <https://doi.org/10.1002/047126363X.agr185>
- Xia Y et al (2024) Effects of soil pH on the growth, soil nutrient composition, and rhizosphere microbiome of Ageratina adenophora. PeerJ 12:e17231. <https://doi.org/10.7717/peerj.17231>
- Xie R et al (2020) Penetration of foliar-applied Zn and its impact on apple plant nutrition status: in vivo evaluation by synchrotron-based X-ray fluorescence microscopy. Hortic Res 7:120. <https://doi.org/10.1038/s41438-020-00369-y>
- Zandonadi CHS et al (2018) Tank-mix of chlorantraniliprole and manganese foliar fertilizers: Impact on rheological characteristics, deposit properties and cuticular penetration. Crop Prot 106:50–57. <https://doi.org/10.1016/j.cropro.2017.12.011>
- Zandonadi CHS et al (2019) Tank mixture of pesticides and foliar fertilizers for *Triozoida limbata* control in guava trees (*Psidium guajava* L.). Rev Ceres 66:297–306. <https://doi.org/10.1590/0034-737X201966040008>

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