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Integrated computational and field approaches unveil nutrient foliar sprays as sustainable solutions for sugar beet powdery mildew management

M. S. Abbas · Ibrahim S. H. El-Gamal · Samar A. M. Helmy · Reham I. AbdelHamid

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Abstract Sugar beet (*Beta vulgaris* var. *saccharum,* L.), a primary contributor to the worldwide sugar market, suffers severely from powdery mildew caused by *Erysiphe betae*, which reduces the photosynthetic efficiency and therewith yields. This study presents molecular docking analysis and randomized complete block design (RCBD) field trials with nutrient foliar sprays to identify disease management strategies. The interaction study in silico analysis using AutoDock Vina indicated tight-binding interactions of metal sulfates with the chitinase enzyme that degrades the fungal cell wall, where the metal sulfates $MgSO_4$ (-4.03 kcal/mol) and $ZnSO_4$ (-3.88 kcal/mol) exhibited significant inhibitory effects. Under natural infection conditions for field validation, a significant reduction in disease severity was observed using copper sulfate (81.56% reduction), comparable to a commercial fungicide. Foliar applications of nutrients improved agronomic traits. Root yield increased by 38% and total sugar yield by 90% compared to un-treated controls. Biochemical analysis revealed significantly enhanced defense responses, including elevated levels of total phenols (76% increase with Copper Sulphate), increased enzymatic activities (peroxidase up to 0.482 U/min/g and catalase up to 0.725 U/min/g), higher protein content (up to 11.29 mg/g), and enhanced proline accumulation (up to 3.54 mg/g) compared to controls. This study highlights the promise of nutrient foliar applications as an environmentally sustainable approach that could replace conventional fungicides to control powdery mildew in sugar beet production.

Keywords Sugar beet · *Erysiphe betae* · Powdery mildew · Nutrient foliar sprays · Molecular docking · Disease resistance · Induced systemic resistance · Crop productivity

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M. S. Abbas
Department of Pests and Diseases Research, Sugar Crops Research Institute, Agricultural Research Center, Giza, Egypt
e-mail: magedscri9@yahoo.com

I. S. H. El-Gamal · S. A. M. Helmy · R. I. AbdelHamid (✉)
Department of Physiology and Biochemistry Research, Sugar Crops Research Institute, Agricultural Research Center, Giza, Egypt
e-mail: RehamIbrahim@agr.asu.edu.eg; rehamezz78@gmail.com

I. S. H. El-Gamal
e-mail: edr.ibrahim66@gmail.com

S. A. M. Helmy
e-mail: Samer20222@yahoo.com

Introduction

Sugar beet *(Beta vulgaris* var. saccharum, L.*)* is an important crop grown mainly for its high sucrose

content, a significant source of sugar for human consumption and industrial applications (Tayyab et al., 2023). In addition to economic significance, sugar beet contributes to food security by being a source of micronutrients and is an integral part of the agricultural economy in several areas (Sekaran et al., 2021). Pathogens, notably fungal diseases including powdery mildew, are increasingly impacting on sugar beet yield. Several fungal pathogens can induce this disease, which presents itself as white, powdery-looking lesions on the leaves and stems of plants and reduces photosynthetic capacity dramatically, resulting in significant losses of crop yield and quality (Misra et al., 2022).

For sugar beet producers, powdery mildew management is a major challenge; thus, it is important to develop effective control strategies against it. The management of such diseases primarily depends on synthetic fungicides; however, their extensive use causes concerns about environmental sustainability, health risks, and pathogen resistance (Tleuovaet al., 2020). Hence, there is an increasing demand for alternative strategies to control fungal diseases with fewer adverse environmental effects. The use of nutrient foliar sprays for disease control has received recent attention (Bamisileet al., 2021). Not only do these treatments supply the important nutrients necessary for plant growth, but they also offer disease resistance by strengthening plants against biotic stressors. Nutrient elements like copper and zinc have antifungal properties; therefore, they are considered good candidates for integrated pest management (IPM) programs (López-Gálvez et al., 2021).

Fungi produce a class of enzymes known as chitinases that are critical for maintaining the integrity of the fungal cell wall; therefore, targeting these enzymes may represent an effective strategy to combat fungal pathogens (Sharma et al., 2020). Molecular docking studies have been successfully conducted to search for possible anti-chitinase compounds. As chitinase has a wide array of ligands with varying degrees of binding affinities, finding compounds that could bind well to the enzyme can lead to promising inhibitors (Czestkowskiet al., 2024). Here, we investigate the effectiveness of nutrient foliar spray applications on powdery mildew control in sugar beet using molecular docking analyses and field observations. This study aims to provide information for sustainable agricultural practices by elucidating the structural interactions between metal sulfates and chitinase and evaluating how these nutrient treatments affect the severity of disease and crop performance. These findings will ultimately contribute to developing strategies that improve disease resistance and crop production while minimizing the use of traditional synthetic fungicides.

Our findings highlight the potential for using foliar sprays as crop protection measures and provide a theoretical basis for molecular docking studies aimed at inducing nutrient application methods that validate long-term sustainability.

Materials and methods

Molecular studies

Protein preparation

The 3D structure of *Homo sapiens* chitinase **(UniProt ID: Q96VN1)**. Non-protein atoms (crystallographic waters, ligands, ions) were removed using AutoDockTools 1.5.6 (Morris et al., 2009). Polar hydrogens were added, non-polar hydrogens merged, and Gasteiger charges assigned. The protein structure was energy-minimized using the Amber ff14SB force field in UCSF Chimera (Pettersen et al., 2004) to resolve steric clashes.

Ligand preparation

Ligand structures were retrieved from the **PubChem database** (Kim et al., 2021) and prepared through **Avogadro 1.2.0** (Hanwell et al., 2012; O'Boyle et al., 2011). Preparation involved adding hydrogen atoms, assigning Gasteiger partial charge, and energy minimization using **Universal Force Field (UFF)** (Rappe et al., 1992).

Predicting binding sites

Potential binding sites on the chitinase protein were identified via the **CB-Dock2** web server (Liu et al., 2022), a deep learning-based approach for predicting binding pockets and cavities.

Molecular docking

Molecular docking simulations were performed using **Auto Dock 4.2** (Shib et al., 2021) with a genetic algorithm. Grid maps for the predicted binding site were calculated using Auto Grid 4, with a grid box size of 20 Å×20 Å×20 Å and a grid spacing of 0.375 Å. The docking parameters were set as follows:

- Population Size: 500
- Maximum Evaluations: 2,500,000
- Maximum Generations: 27,000 A maximum of 10 conformations per ligand were generated, with rankings based on the estimated binding free energy.

Field experiment

Experimental design

Two field experiments were conducted on sugar beet at Sakha Research Station (latitude of 31°05′39"N and a longitude of 30°56′31"E, with an elevation of 4.07 m above sea level), Kafr El-Sheikh Governorate, Egypt, in the 2022/2023 and 2023/2024 seasons. Physical and chemical analysis of the experimental soil was done according to Black et al. (1981) and Jackson (1973). As an average of the two growing seasons, the analysis showed that the soil texture was clayey, having 12.3% sand, 33.3% silt, 54.4% clay, and 1.12% organic matter, with an electrical conductivity (EC) of 1.4 dSm^{-1}, and a pH of 8.2. The available macronutrients were: 38.9, 9.9, and 209 mg kg^{-1} soil for N, P_2O_5, and K_2O, respectively. The available micronutrients were: 1.2 ppm zinc, 6 ppm copper, and 0.42 ppm boron.

Multi-germ sugar beet variety, viz. Hilospoly (susceptible to powdery mildew, Salama, 2021) was sown in the 2nd week of September, following maize, while harvesting was done at 210 days, in both seasons. Beet plants were thinned at the 4-true-leaf stage to ensure one plant/hill. Phosphorus fertilizer was applied as calcium superphosphate (15% P_2O_5) at a rate of 72 kg P_2O_5/ha during seedbed preparation. Nitrogen fertilizer was added at 216 kg N/ha using ammonium nitrate (33.5% N) in two equal doses, after thinning, and the 2nd one month later. Potassium fertilizer was used as potassium sulphate (48% K_2O) at a rate of 57.6 kg K_2O/ha, which was split into two equal doses, coinciding with the 1st and 2nd doses of nitrogen fertilizer. A randomized complete block design (RCBD) with three replicates was used. Each plot consisted of 21 m^2 (5 ridges with 7 m length, 60 cm width, and hill spacing of 20 cm). All other field practices were conducted as recommended by the Sugar Crops Research Institute, Agricultural Research Center, Egypt.

Foliar applications

At 70, 85, and 100-day post-planting, foliar applications were performed to apply the necessary nutritional elements at specified concentrations. The foliar spray treatments were; 0.5% ferrous sulphate ($FeSO_4.7H_2O$), 0.5% zinc sulphate ($ZnSO_4.7H_2O$), 0.5% manganese sulphate ($MnSO_4.H_2O$), 0.5% copper sulphate ($CuSO_4.5H_2O$), and 0.5% potassium bicarbonate ($KHCO_3$), 2% magnesium sulphate ($MgSO_4.7H_2O$), 1% boric acid (H_3BO_3), 1% calcium chloride ($CaCl_2$), 0.02% ammonium molybdate [$(NH_4)_6Mo_7O_{24}.4H_2O$], and a fungicide treatment (Score, containing 25% EC difenoconazole) which was sprayed at a rate of 0.5 ml L^{-1}, as compared to the control treatment with tap water.

Data collection

Disease assessment Disease severity was estimated two weeks after the last treatment application by assessing 50 plants per plot according to the (Whitney et al., 1983) scale. On a scale of 0–4 (0 = no mildew colonies observed; 1 = 1–25% leaf area; 2 = 26–50% leaf area; 3 = 51–75% leaf area; and 4 = 76–100% leaf area affected), we determined the severity of mildew in each treatment group.

Morphological and physiological characteristics After two weeks from the last foliar application, a sample of ten plants was randomly taken from the guarded ridges of each plot to determine total chlorophyll content (mg/g fresh weight), which was quantified from the leaf sample according to Arnon (1949). At harvest, specific leaf weight (g/cm^2) according to Misra et al. (2017), as well as top and root fresh weights/plant (g), were measured.

Biochemical assessment Ten plants were randomly taken from each plot's guarded ridges two weeks after the last foliar treatment to estimate total phenols (mg/g fresh weight) according to Bray and Thrope (1954). Peroxidase activity (U/min./g f.w.) was evaluated based on the modification of (Allam & Hollis, 1972), measuring spectrophotometric alterations throughout substrate oxidation. Catalase activity (U/min./g f.w.) was determined using the spectrophotometer method of Maxwell and Bateman (1967). Amino acids (g/100 g protein) analysis was conducted using the method described by Jeong and Shim (2004). Proline (mg/g f.w.) was calculated using Bates et al. (1973) protocol through colorimetric assays. Crude Protein (mg/g f.w.) = Total Nitrogen × 6.25, according to A.O.A.C. (2005). These analyses revealed a biochemical response profile of the treated sugar beet plants.

Quality parameters At harvest, ten roots per plot were sampled to measure several quality traits. Sucrose % was measured according to A.O.A.C. (1995). Purity % was calculated using Devillers (1988) equation; Purity % = 99.36—[14.27 (Na + K + α amino N)/sucrose. Sugar lost to molasses % (SLM) was computed as described by Devillers (1988) using the equation; SLM = [0.14 (Na + K) + 0.25 (α amino N) + 0.5]. Extracted sugar% was calculated by the equation: Extracted sugar % = sucrose %—SLM—0.6, according to Dexter et al. (1967). Sugar reduction was assessed using the **A.O.A.C.** method (1990). Root impurities in terms of α-amino N, Na, and K (meq/100 g beet) were determined following A.O.A.C. (2005) methods.

Yields Root and top yields/fed (ton) were determined at harvest. Sugar yield/fed (ton) was calculated according to the following equation:

$$\text{Sugar yield/fed (ton)} = \text{Root yield/fed (ton)} \times \text{Extracted sugar \%}$$

Where: fed = 0.42 $ha.^{-1}$

Statistical analysis

All obtained data were statistically analyzed using the MSTAT-C computer software package. For the randomized complete block design published by Gomez & Gomez (1984), analysis of variance (ANOVA) was used. The least significant difference (LSD) method was used to test the differences between treatment means at a 5% probability level as described by Snedecor and Cochran (1980).

Graph creation

The experimental data were processed and visualized using Python version 3.x in the Google Colab environment. For data analysis and graphical representation, several key libraries were utilized. Matplotlib (version 3.x) was to create comprehensive data visualizations, including static, animated, and interactive plots. Additionally, NumPy (version 1.x) was used for numerical computations and array manipulations, essential for efficient data handling and processing. These libraries facilitated the generation of various types of plots, such as line charts, bar charts, and histograms, thereby enabling the presentation of complex data clearly and insightfully.

Results

Molecular docking analysis

Molecular docking simulations were performed to assess the binding affinity of the tested nine nutrient compounds, which exhibited potent activity against chitinase phosphorylases **(UniProt ID: Q96VN1)** as evidenced through molecular docking, thus establishing them as potential anti-chitinase agents for powdery mildew. The binding energies of all nine compounds used in this study, listed in Table 1, range from −4.03 to −0.95 kcal/mole, both of which have inhibitory potential toward chitinase. Magnesium sulfate ($MgSO_4$) had the most favorable binding energy (−4.03 kcal/mol) and inhibition constant (Ki = 1.11 mM), while zinc sulfate ($ZnSO_4$) showed strong binding with lipase (−3.88 kcal/mol and Ki = 1.43 mM).

Structure–activity relationships

The strong binding via unique structural properties and ionic interactions of the metal sulfates must be

Table 1 Docking result for nutrient elements with Chitinase

Ligand	ΔG(Kcal/Mol)	Inhibition constant Ki
Magnesium Sulphate ($MgSO_4$)	−4.03	1.11 mM
Zinc Sulphate ($ZnSO_4$)	−3.88	1.43 mM
Manganese Sulphate ($MnSO_4$)	−3.64	2.13 mM
Ferrous Sulphate ($FeSO_4$)	−3.58	2.39 mM
Copper Sulphate ($CuSO_4$)	−3.40	3.24 mM
Potassium Bicarbonate ($KHCO_3$)	−2.27	21.77 mM
Calcium Chloride ($CaCl_2$)	−2.09	29.33 mM
Boric acid (H_3BO_3)	−1.03	176.83 mM
Ammonium Molybdate ($(NH_4)_6Mo_7O_{24}$)	−0.95	199.85 mM

credited for their high binding affinities Fig. 1. The interaction of magnesium and zinc sulfate, in particular, seems strong and suggests that specific molecular recognition of these ions takes place in the active site. Both manganese, ferrous sulfates and copper sulphate showed good binding (−3.64 kcal/mole, Ki = 2.13 mMt, −3.58 kcal/mole, Ki = 2.39 mM, and −3.40 kcal/mole, Ki = 3.24 mM, respectively) Fig. 2.

Therapeutic implications and future directions

The wide range of binding energies (−4.03 to −0.95 kcal/mol) that the tested compounds displayed provides information about potential optimization strategies for the future. After identifying potential leads for a new class of bio-fungicides in a computational manner, we then applied our new class of molecules under field conditions in sugar beet crops (described in the next section) to corroborate the bioactivity of the compounds identified computationally. Guided by our integrated computational and field experimental approach, future investigations should focus on:

1. Investigating the synergistic effects of combining strong and moderate binding compounds
2. Further evaluating the practical applications of metal sulfates in diverse agricultural settings beyond sugar beet
3. Developing formulations that optimize bioavailability while maintaining crop safety

This comprehensive analysis, supported by our field validation studies on sugar beet, establishes a strong foundation for developing targeted anti-chitinase treatments. Metal sulfates show particular promise as effective agents against powdery mildew in computational predictions and agricultural applications.

Impact of nutrient foliar sprays on disease resistance and growth performance of sugar beet

The study, which is referred to in Supplemental Table 1 and Fig. 3, aimed to assess the impact of different nutrient foliar applications on sugar beet resistance to powdery mildew and plant performance at two consecutive seasons **(2022/2023 and 2023/2024)**.

The analysis of disease severity showed a statistically significant difference between treatments, in which the lowest levels of infection (1.75–2.83%) observed were in the groups treated with fungicide score and copper sulphate (untreated control group infection levels 13.33–15.58%). Assessments of chlorophyll content indicated increased potential for photosynthesis between nutrient treatments, and copper and zinc sulphate resulted in the highest levels of chlorophyll per g f.w (4.99–5.27 mg/g f.w) over the untreated control (3.62–3.77 mg/g f.w). Specific leaf weight improved, especially between copper and zinc sulphate treatments, where values increased as a result of the treatments from the control 0.304–0.382 g/cm^2 to 0.608–0.639 g/cm^2.

Plant biomass parameters showed a significant increase. Overall, top fresh weight was increased by 70–90%, from 142–143 g/plant in the Untreated control to 250–276 g/plant in the copper sulphate treatments. Likewise, root fresh weight increased from 760–763 g/plant in control to 1049–1073 g/plant in copper sulphate treatments, reflecting a 35–40% increase in root productivity.

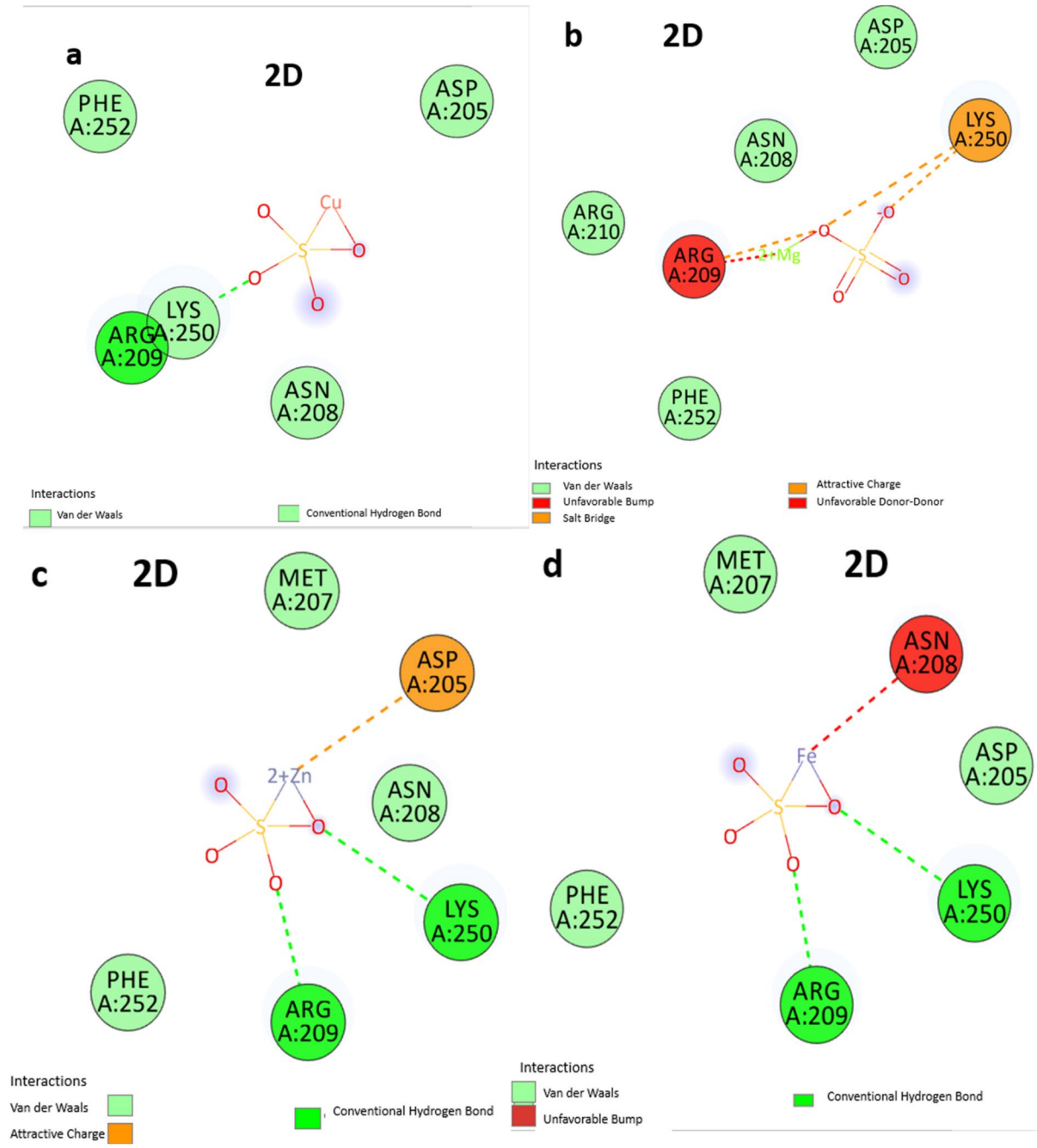


Fig. 1 Docking interaction between Chitinase and (**a**) $CuSO_4$ (**b**) $MgSO_4$ (**c**) $ZnSO_4$ (**d**)$FeSO_4$

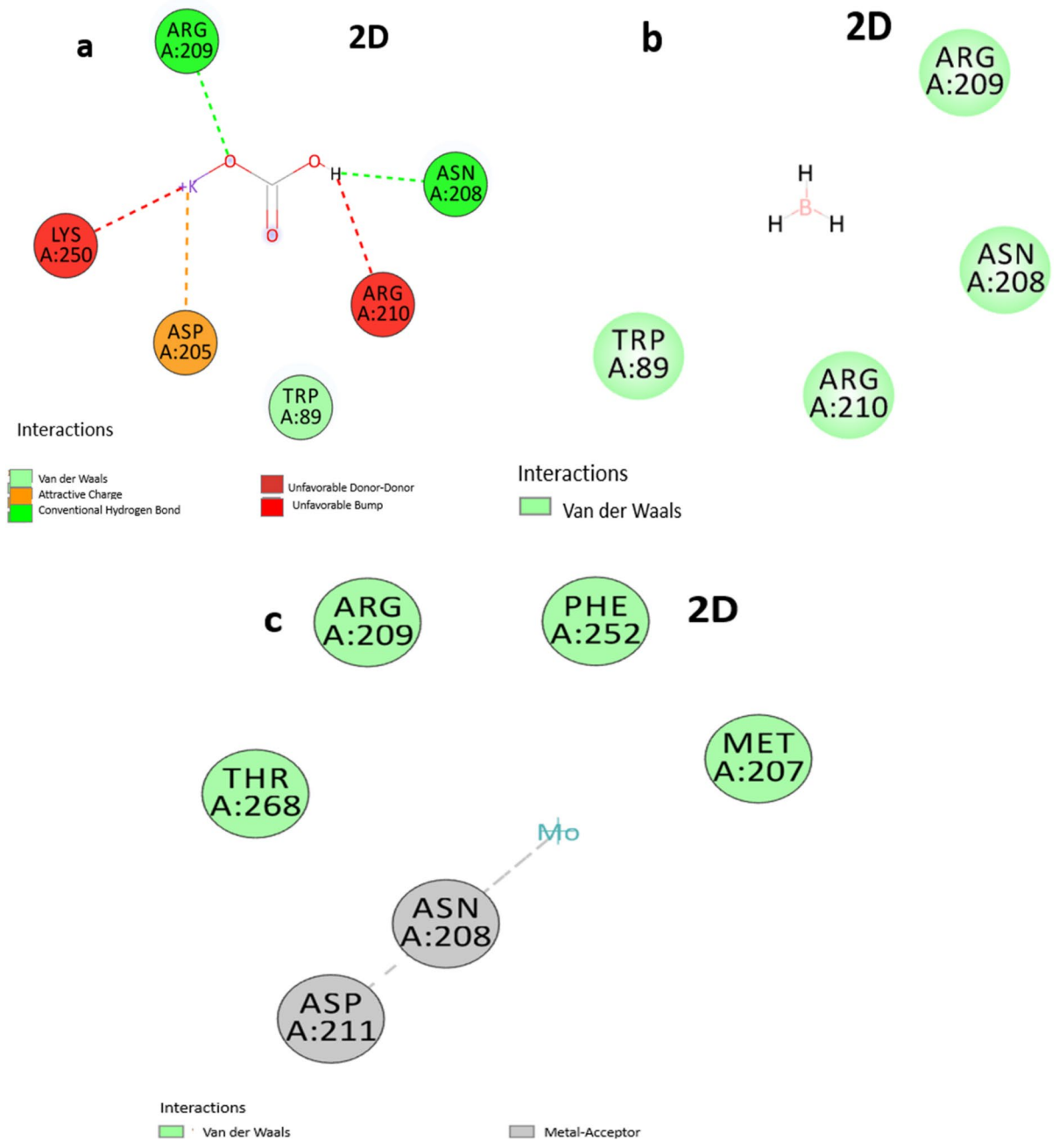


Fig. 2 Docking interaction between Chitinase and (**a**) $KHCO_3$ (**b**) H_3BO_3 (**c**) $(NH_4)_6Mo_7O_{24}$

Impact of nutrient treatments on biochemical and physiological responses in plants

As illustrated in Fig. 4 and Supplemental Table 2, our study of prominent trends in plants' biochemical and physiological responses to the full range of foliar nutrient treatments and fungicide applications was reported throughout the **2022/2023** and **2023/2024** experimental seasons. The heatmap visualization indicates treatment efficacy using an intensity gradient, with deeper color shading indicating more positive responses than the untreated control.

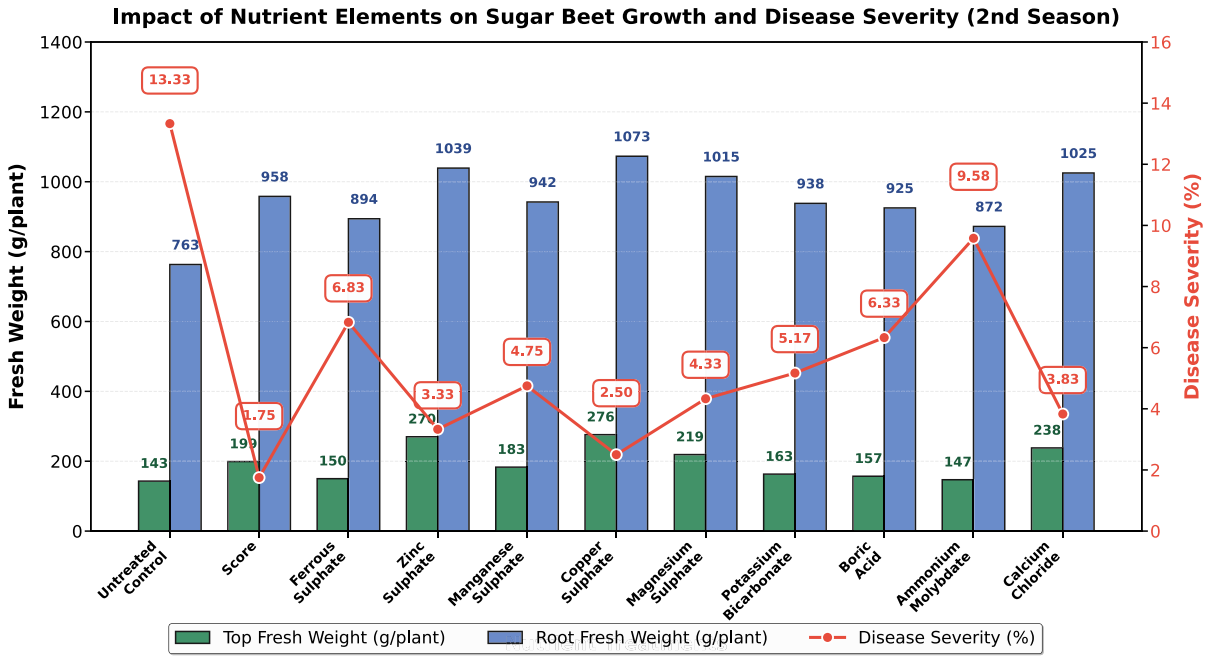


Fig. 3 Impact of Nutrient Elements on Sugar Beet Growth and Disease Severity

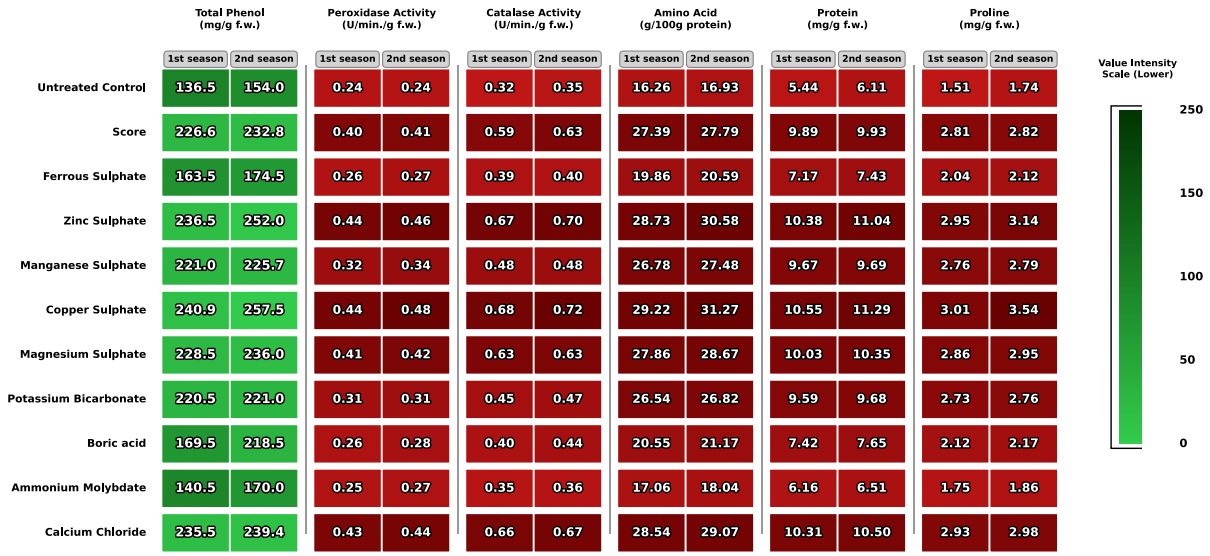


Fig. 4 Heatmap analysis of biochemical responses in sugar beet plants under different foliar treatments during the 2022/2024 season. Color intensity (green: high, red: low) represents values across six biochemical parameters, revealing treatment efficacy hierarchy with Copper Sulphate showing the most pronounced positive responses

Total phenol content

The heatmap Fig. 4 shows that micronutrient treatments, except Copper Sulphate and Zinc Sulphate, were the most effective in increasing total phenol content compared to the control. Following Copper Sulphate with the highest increase at (240.9 mg/g and 257.5 mg/g in first and second seasons) were Zinc

Sulphate (236.5 mg/g and 252.0 mg/g) and Calcium Chloride (235.5 mg/g and 239.4 mg/g), when compared with the untreated control (136.5 mg/g and 154.0 mg/g).

Enzymatic activities

Figure 4 demonstrates coordinated enhancement in enzymatic responses across treatments. Both peroxidase and catalase activities showed marked increases under mineral treatments, particularly with Copper Sulphate (0.443 to 0.482 U/min/g for peroxidase and 0.677 to 0.725 U/min/g for catalase) and Zinc Sulphate (0.440 to 0.459 U/min/g for peroxidase and 0.672 to 0.698 U/min/g for catalase).

Amino acid and protein content

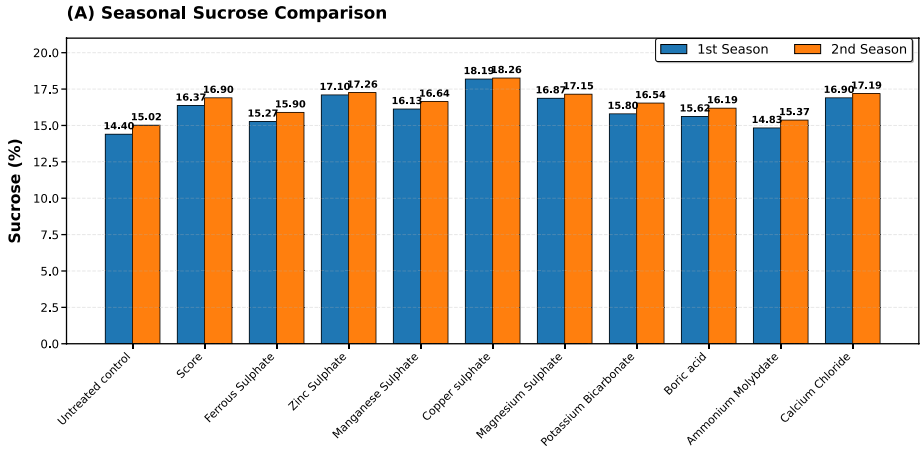
The color gradients in Fig. 4 display a unique pattern between amino acid and protein synthesis over the treatment conditions. Of the treatments investigated, Copper Sulphate showed the most pronounced impact on the amino acid content (29.22 g/100g protein in the first season and 31.27 g/100g protein in the second season), with second-best results recorded for Zinc Sulphate (28.73 to 30.58 g/100g protein) and Calcium Chloride (28.54 to 29.07 g/100g protein). Similar trends were observed with protein content: Copper Sulphate (10.55 to 11.29 mg/g) followed by Zinc Sulphate (10.38 to 11.04 mg/g).

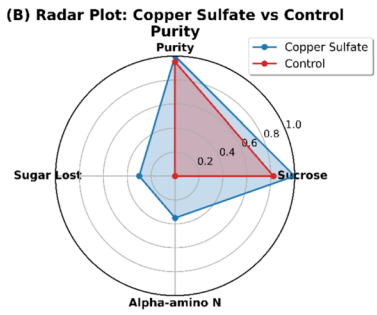
Proline levels and stress tolerance

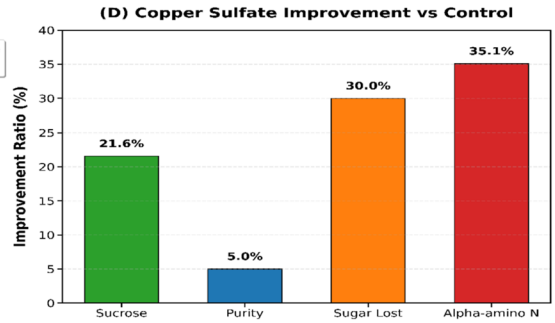
The bottom row of Fig. 4 shows the important difference in the proline amount between treatments. The most intense green color that provide the highest levels of proline (3.01 mg/g to 3.54 mg/g) was observed in treatments of Copper Sulphate whereas, Zinc Sulphate and Calcium Chloride followed the Copper Sulphate with a proline level of 2.95 mg/g to 3.14 mg/g and 2.93 mg/g to 2.98 mg/g respectively when compared to the untreated control where it was 1.51 mg/g to 1.74 mg/g. The heatmap visualization in Fig. 4 effectively demonstrates a clear hierarchy of treatment efficacy. Copper Sulphate consistently shows the most potent positive effects across all parameters, followed closely by Zinc Sulphate and Calcium Chloride. Other treatments, such as Magnesium Sulphate and Score fungicide, showed moderate effectiveness, while treatments like Ammonium Molybdate and Boric acid demonstrated relatively lower impacts.

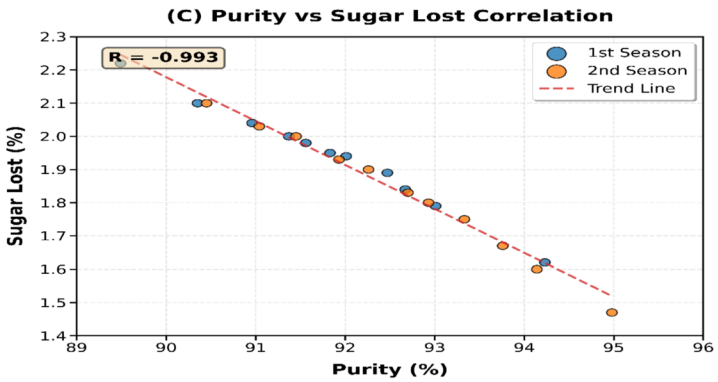
Sugar beet quality parameters and processing efficiency under various nutrient treatments

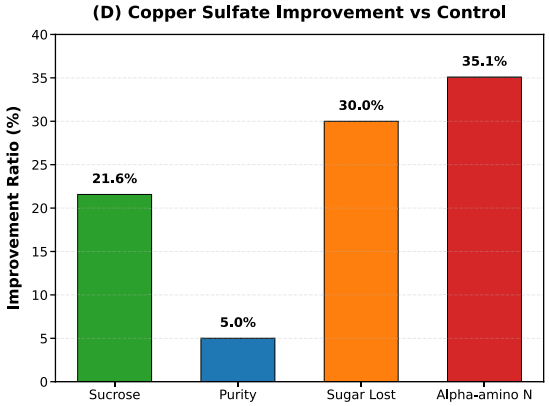
Sugar content and quality parameters As shown in Supplemental Table 3 and Fig. 5A-D, the highest sucrose concentration was achieved with the copper sulfate treatment, reaching 18.19% and 18.26% in the first and second seasons, respectively (Fig. 5A**).** This represents a substantial 24.0% increase compared to the untreated control (14.40% and 15.02%). Zinc sulfate treatment also demonstrated strong performance, yielding 17.10% and 17.26% sucrose content across both seasons. The bar chart in Fig. 5A clearly displays these numerical values on each bar, showing the consistent superiority of copper and zinc treatments throughout both growing periods. The quality parameter comparison in Fig. 5B provides a comprehensive view of key metrics, where copper sulfate treatment exhibited the highest values across all parameters. Purity percentages peaked at 94.23% and 94.98% for the copper sulfate treatment compared to control values of 89.49% and 90.45% (Supplemental Table 3). Zinc sulfate treatments also achieved high purity levels of 93.01% and 94.14%. The numerical values displayed directly on the bars in Fig. 5B confirm the superior performance of these treatments. Figure 5C illustrates the strong inverse relationship between purity and sugar loss, showing a very high negative correlation ($r = -0.995$, $P < 0.001$) where increased purity corresponds to reduced sugar loss. Sugar loss to molasses was minimized with copper sulfate treatment (1.62% and 1.47%) compared to the control (2.22% and 2.10%). The improvement ratios in Fig. 5D quantify the efficacy of copper and zinc sulfate treatments relative to the control, demonstrating significant enhancements across all quality parameters. Copper sulfate showed 24.0% improvement in sucrose content, 34.6% in extracted sugar, and −28.2% reduction in sugar loss (negative indicating beneficial reduction). Extracted sugar percentages were highest for copper sulfate treatment (15.97% and 16.19%) compared to control values (11.58% and 12.31%).


(A) Seasonal Sucrose Comparison
1st Season
2nd Season
Sucrose (%)
14.40
15.02
16.37
16.90
15.27
15.90
17.10
17.26
16.13
16.64
18.19
18.26
16.87
17.15
15.80
16.54
15.62
16.19
14.83
15.37
16.90
17.19
Untreated control
Score
Ferrous Sulphate
Zinc Sulphate
Manganese Sulphate
Copper sulphate
Magnesium Sulphate
Potassium Bicarbonate
Boric acid
Ammonium Molybdate
Calcium Chloride


(B) Radar Plot: Copper Sulfate vs Control
Purity
Copper Sulfate
Control
Sugar Lost
Sucrose
Alpha-amino N


(D) Copper Sulfate Improvement vs Control
Improvement Ratio (%)
21.6%
5.0%
30.0%
35.1%
Sucrose
Purity
Sugar Lost
Alpha-amino N


(C) Purity vs Sugar Lost Correlation
R = -0.993
1st Season
2nd Season
Trend Line
Sugar Lost (%)
Purity (%)


(D) Copper Sulfate Improvement vs Control
Improvement Ratio (%)
21.6%
5.0%
30.0%
35.1%
Sucrose
Purity
Sugar Lost
Alpha-amino N

◂**Fig. 5** Nutrient treatment effects on sugar beet quality: (**A**) Sucrose content, (**B**) Quality parameters, (**C**) Purity-sugar loss correlation ($r = -0.995$), (**D**) Improvement percentages. Copper sulfate showed superior performance across all metrics. Statistical significance: $P < 0.05$

Reducing sugars and impurity profiles Copper and zinc sulfate treatments resulted in the lowest reducing sugar levels (0.45–0.49%), significantly below control levels (0.89% and 0.80%), as shown in Supplemental Table 3. These results align with Makhlouf et al. (2022), who documented similar nutrient effects on carbohydrate metabolism.

Impurity profiles presented in Supplemental Table 4 consistently showed lower levels in treated groups. Copper sulfate treatment substantially reduced alpha-amino nitrogen content (1.81 and 1.72 meq/100g) compared to the control (2.96 and 2.65 meq/100g), representing a 37.0% reduction. Similar reductions were observed for potassium (3.13 and 2.40 meq/100g vs control 4.52 and 4.46 meq/100g) and sodium content (1.60 and 1.49 meq/100g vs control 2.49 and 2.26 meq/100g). The integrated data from Supplemental Tables 3 and 4, combined with the visualisations in Fig. 5, demonstrate that copper sulfate treatment consistently produced the most favourable outcomes across all quality parameters, followed by zinc sulfate treatment. The numerical values presented in the tables and figures provide clear evidence that targeted nutrient applications can significantly enhance sugar beet processing efficiency and final product quality, with copper sulfate showing particularly strong performance in improving sucrose content and purity and reducing processing losses. The exceptionally strong correlation ($r = -0.995$) shown **in** Fig. 5C underscores the reliability of purity as an indicator of overall sugar beet quality.

Effects of different nutrient treatments on sugar beet yield parameters

The effects of different nutrient treatments on sugar beet yield parameters were studied over two consecutive growing seasons (the data are presented in Supplemental Table 5 and illustrated through several visualisations in Fig. 6A-C to facilitate a comprehensive understanding.

Root yield

The relationship between root yield and sugar yield is presented in the scatter plot of Fig. 6C, which highlights the strong positive correlation between these parameters across treatments. Copper sulphate consistently yielded the highest root production at 34.96 and 35.76 tons feddan^{-1} (equivalent to 83.24 and 85.14 tons/ha, respectively), representing a 38.1% increase over the control (25.33 and 25.44 tons feddan^{-1}, equivalent to 60.31 and 60.57 tons/ha, respectively). Both zinc sulphate (33.94 and 34.63 tons feddan^{-1}) and calcium chloride (33.39 and 34.17 tons feddan^{-1}) also resulted in significantly higher root yields compared to the control. The clustering pattern in the scatter plot clearly demonstrates that treatments with higher root yields generally correspond to higher sugar yields, emphasizing the importance of balanced nutrient management for maximizing overall production.

Top yield

The comparative performance of top yields across treatments is visualised through donut charts in Fig. 6B, clearly displaying both proportional distribution and absolute values for each treatment. Copper sulphate treatment demonstrated exceptional efficacy, yielding 8.33- and 9.20-ton feddan^{-1} (equivalent to 19.83 and 21.90 tons/ha, respectively) in the first and second seasons. This represents a 76.1% increase over the untreated control, which produced 4.73- and 4.78-ton feddan^{-1} (equivalent to 11.26 and 11.38 tons/ha, respectively). Zinc sulphate treatment also showed substantial improvement, yielding 7.16- and 9.01-ton feddan^{-1} (equivalent to 17.05 and 21.45 tons/ha, respectively). The visual representation clearly shows the dominance of copper and zinc treatments, which collectively accounted for the highest top yield biomass in both seasons.

Sugar yield

Analysis of sugar yield demonstrated substantial improvements under nutrient supplementation compared to the untreated control. The heatmap visualisation in Fig. 6A uses a colour gradient scale where intense yellow colours indicate higher yields and purple colours indicate lower yields, creating a clear

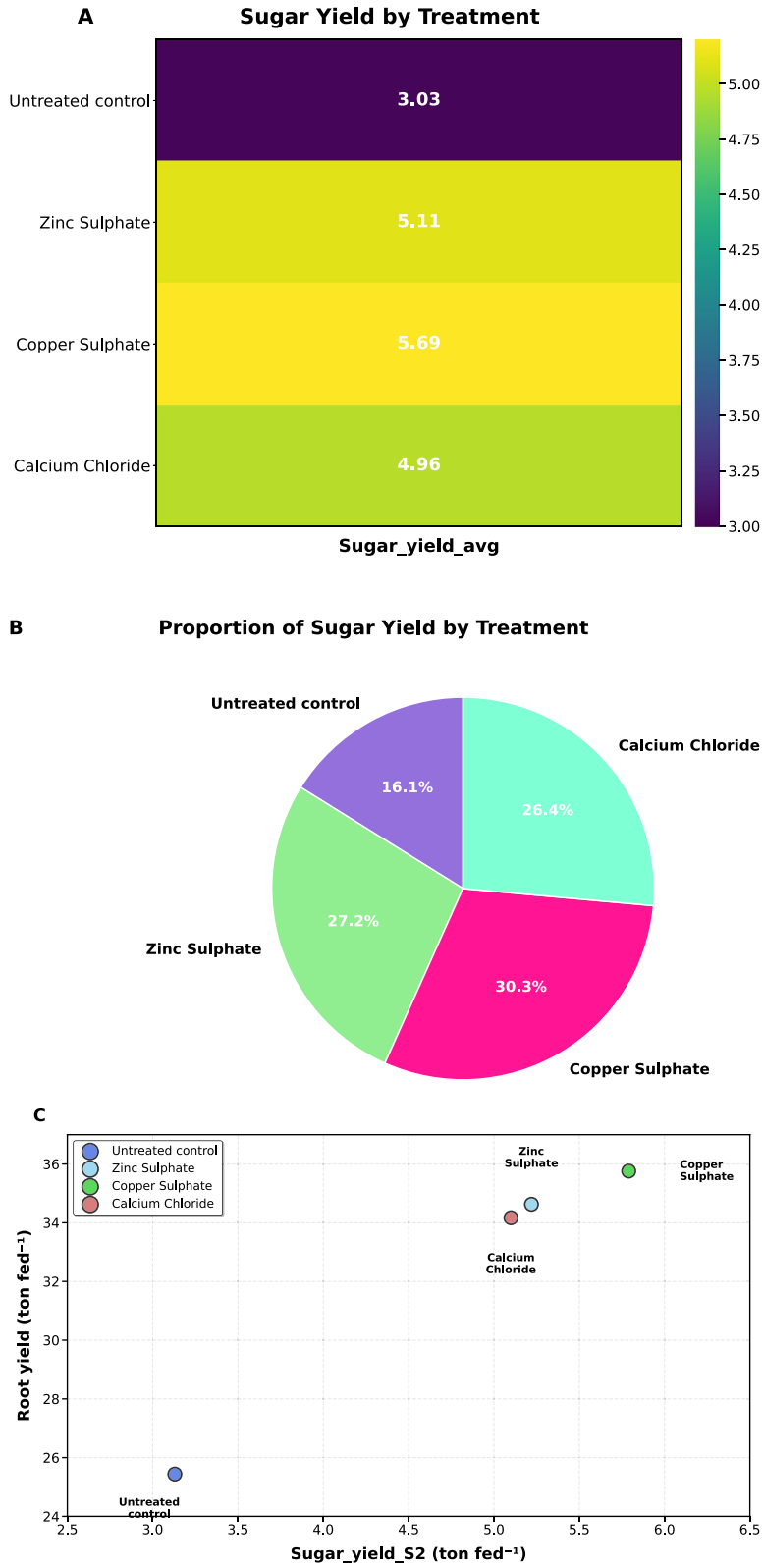


Fig. 6 Effects of different nutrient treatments on sugar beet (Beta vulgaris L.) yield parameters across two consecutive growing seasons. (**A**) Heatmap of sugar yield (ton feddan^{-1}) with a yellow-to-purple gradient, where yellow indicates higher yields. (**B**) Comparative top yield distribution among major treatments shown as donut charts with absolute values. (**C**) Scatter plot illustrating the relationship between root yield and sugar yield across treatments

visual hierarchy of treatment efficacy. Copper sulphate emerged as the most effective treatment, represented by the brightest yellow colour on the heatmap, producing sugar yields of 5.58 and 5.79 tons feddan^{-1} (equivalent to 13.28 and 13.78 tons/ha, respectively) in the first and second seasons. This represents a 90.4% increase over the control values of 2.93 and 3.13 tons feddan^{-1} (equivalent to 6.97 and 7.45 tons/ha, respectively), which appear in the darkest purple on the heatmap, visually emphasising the performance gap. Zinc sulphate (4.99 and 5.22 tons feddan^{-1}) and calcium chloride (4.83 and 5.10 tons feddan^{-1}) also exhibited strong performance, shown in intermediate shades, confirming their consistent efficacy across both seasons.

Discussion

Mechanistic implications

The high binding affinities achieved with metal sulfates suggest a coordination bond formation between the metal ions of the enzyme and the amino acid residues on the enzyme's active site. The pivotal role of metal ions in enzyme inhibition has previously been noted by a few reports (Umar et al., 2021; Yuan et al., 2020), and our findings aligne with their conclusion. The binding capabilities of the metal sulfide can be defined via the ionic radius, charge density, and electronic organization that determines the inhibiting of these metal sulfates.

Comparative analysis of non-metal compounds

The best activity was shown by the non-metal compound potassium bicarbonate ($KHCO_3$) with a binding affinity of −2.27 kcal/mol (Ki = 21.77 mM), which makes this compound a potential alternative treatment, due to its proven safety in ecological agriculture systems (Mahmud et al., 2021). Next, calcium chloride showed a moderate binding energy of −2.09 kcal/mol (Ki = 29.33 mM). In contrast, boric acid (H_3BO_3) and ammonium molybdate showed lower binding affinities, with values of −1.03 kcal/mol (Ki = 176.83 mM) and −0.95 kcal/mol (Ki = 199.85 mM), respectively. This comparative analysis highlights the varying degrees of interaction strength among these compounds.

Integration of molecular docking with field trials

The combination of molecular docking studies and field experiments represents a modern agricultural approach that forms a strong framework for identifying effective strategies to manage plant diseases. In the present study, molecular docking analysis of different ligands with chitinase **(UniProt ID: Q96VN1)** suggested a substantial role for anti-chitinase agents in controlling powdery mildew in sugar beet. Notably, metal sulfates, especially magnesium sulfate ($MgSO_4$) and zinc sulfate ($ZnSO_4$), exhibited high binding affinities, indicating their capacity to inhibit chitinase activity and thereby compromise the fungal chitin cell wall integrity. These in silico results provided a theoretical foundation for subsequent field trials using nutrient foliar sprays targeting powdery mildew control.

Molecular docking guided the selection of specific nutrient treatments, establishing a direct link between computational predictions and field applications. The strong binding interactions computed between these compounds and their target protein offered confidence in their efficacy, supported by field trial results where copper sulfate treatment reduced disease severity by 81.56%, consistent with its predicted inhibitory potential from the docking analyses. This alignment highlights the value of computational methods as guiding tools in agricultural research, allowing the identification of promising candidates prior to extensive and resource-intensive field experiments. Consequently, researchers can optimize resource allocation and focus on treatments with the highest likelihood of success. Moreover, correlating molecular insights with empirical data enhances understanding of how targeted nutrient interventions can improve disease resistance and overall crop productivity (Pathak et al., 2016; Allam et al., 2025).

Further, integrating molecular docking with field validation underscores this approach's biological efficacy and economic applicability. Docking offers a low-cost predictive tool to pre-select promising compounds, thus reducing experimental costs and increasing efficiency. The consistent results between in silico and field studies confirm the practical value of $MgSO_4$ and $ZnSO_4$ foliar sprays. Significantly, unlike traditional fungicides that act directly on the pathogen and may induce resistance, these nutrient

salts enhance the plant's defence responses, minimising the risk of pathogen adaptation and supporting sustainable disease management strategies. Future studies should aim to optimize application rates and timings across diverse agro-climatic conditions and assess the long-term sustainability of repeated use (Bamisile et al., 2021; Tamm et al., 2022).

Interpretation of field and biochemical results

The significant reduction in disease severity observed with copper sulfate aligns with previous studies showing that copper compounds are antifungal. For example, studies by Tamm et al. (2022) showed that copper-based fungicides suppressed fungal pathogens and contributed to sugar beet yield improvements by affecting the fungus's cell membrane and preventing spore development. Such improvement in disease control aligns with the principle that using nutrient foliar sprays as a supplementary regimen to the currently available fungicide application can positively impact disease control.

The increased chlorophyll content and specific leaf weight indicate that nutrient foliar sprays enhance the photosynthetic capacity, leading to increased growth. A study by Dass et al. (2022) reported that sugar beets treated with micronutrients foliarly showed increased chlorophyll content, causing growth and yield parameters to increase as well. The dramatic increases in top and root biomass recorded in this trial indicate that nutrient foliar sprays could strongly impact overall plant performance, corroborating research on (Ahmed et al., 2024; Salarian & Salari, 2020), which focused on how micronutrients can improve the biomass of plants.

The enhanced level of total phenols indicates a greater potential for pathogen resistance, as per the findings of Liu et al. (2021). The marked increases in peroxidase and catalase activities agree with Mutale-Joan et al. (2021) observations about nutrient-enhanced enzymatic activities. The pronounced impact on amino acid and protein content supports (Dhaliwal et al., 2022) research on micronutrient-enhanced protein synthesis. The elevated proline levels strongly suggest (Reddy et al., 2024) insights into mechanisms that boost stress resilience.

The sucrose content and purity improvements are consistent with Hamzah Saleem et al. (2022), highlighting improved sugar content by copper and zinc application. Micronutrients have also been proven effective in improving sugar quality by reducing non-sugar components (Mekdad & Shaaban, 2020). Reducing sugar loss to molasses corroborates Wei et al. (2022), showing nutrient applications reduce processing losses through improved plant health. The lowest reducing sugar levels align with Makhlouf et al. (2022), who noted similar effects of nutrients on carbohydrate metabolism. The reduced impurity levels support Sardans and Peñuelas (2021) findings on nutrient management benefits.

The yield increases are consistent with Maqbool et al. (2022) and were reflected in the results, with applications of micronutrients significantly improving root growth and development. The improvements in top yield agree with Chowdhury et al. (2021)**,** highlighting an increased physiological process due to appropriate nutrients. Overall crop yield gains show that targeted nutrient supplementation could contribute as much to sugar beet production as any crop variability (Francis et al., 2024).

Conclusion

For the first time, the present study demonstrates the effectiveness of nutrient foliar sprays in accomplishing powdery mildew control and improving the growth performance of sugar beet ***(Beta vulgaris).*** The molecular docking analyses revealed that metal sulfates, particularly $MgSO_4$ and $ZnSO_4$, exhibited strong binding affinities with chitinase, indicating their potential as effective chitinase inhibitors. The efficacy of copper sulfate treatment was confirmed in field trials (81.56% disease severity reduction), second only to that of the standard fungicide Score (87.33% disease severity reduction). The foliar sprays of nutrients proved paramount in enhancing significant agronomic characteristics, such as 38% root yields and 90% total sugar yields. Dramatically enhanced values of phenol content, enzymatic activities, and protein synthesis were revealed in the biochemical results. Chlorophyll content measurements further exhibited higher values across all treatments, with copper and zinc sulfates exhibiting a significantly more substantial effect on photosynthetic potential. Statistical analyses validated the significance of these findings, further highlighting the promising potential of nutrient foliar applications as sustainable substitutes for conventional chemical fungicides. Though the Score fungicide

was proven to be the most effective for disease control, some nutrient elements (most notably copper and zinc sulfates) showed good potential for disease suppression and overall plant health enhancement. The study also emphasizes collaboration between in silico docking experiments and field exposure to find ideal management for effectively controlling crop diseases. Integrating these molecular insights with the field of empirical data illustrates the importance of contemporary approaches in agricultural research, allowing for the development of more sustainable practices that have the potential to increase disease resistance while simultaneously boosting crop productivity. Future work should aim to optimize application rates and identify synergistic or antagonistic effects between various nutrient treatments to promote the efficiency of these inputs in diverse agricultural ecosystems.

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Author contributions **Maged S. Abbas and Ibrahim S. H. El-Gamal:** Designed and conducted field experiments, performed agronomic and physiological data collection, analyzed field data, and provided the sugar beet cultivar (Hilospoly). Contributed to methodology validation and manuscript review.

Samar A.M. Helmy: Assisted in statistical analysis of experimental data and manuscript review.

Reham I. AbdelHamid: Conceptualized the study, designed and executed molecular docking experiments, performed bioinformatics analysis (protein/ligand preparation, binding site prediction), interpreted computational and biochemical data, visualized results, wrote the original draft, and coordinated manuscript revisions.

All authors: Reviewed and edited the manuscript, approved the final version for publication, and agreed to be accountable for all aspects of the work.All authors reviewed, edited, and approved the final version of the manuscript for publication.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate There is no ethical issue in this research.

Consent to publish All authors consent to the publication of the manuscript.

Clinical trial Not applicable.

Conflict of interest There is no conflict of interest among the authors.

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References

A. O. A. C. (2005) Association of Official Analytical Chemists. "Official Methods of Analysis", 16th ed. Inter. Washington, D. C. USA.

A. O. A .C. (1990) Official methods of Analysis, Association of Official Analytical Chemistry 15th Edition.

A. O. A.C. (1995). Association of Official Analytical Chemists. Official methods of analysis, 16th Ed. A.O.A.C. International, Washington, D.C., USA.

Ahmed, N., Zhang, B., Chachar, Z., Li, J., Xiao, G., Wang, Q., Hayat, F., Deng, L., Narejo, M.-u-N., Bozdar, B., & Tu, P. (2024). Micronutrients and their effects on horticultural crop quality, productivity, and sustainability. *Scientia Horticulturae, 323*, Article 112512.

Allam, A. I., & Hollis, S. P. (1972). Sulfide inhibition of oxidase in rice root. *Phytopathology, 62*, 634–636.

Allam, K. S., Magdy, M., El-Aal, A. A., Khalil, N. S., Rashed, M. A., Atta, A. H., & AbdelHamid, R. I.(2025). Molecular docking and differential rbcl gene expression reveal variation in glyphosate herbicide tolerance of sugarcane varieties. *Molecular Biology Reports*, *52*(1), 168. https://doi.org/10.1007/s11033-025-10274-z

Arnon, D. I. (1949). Copper enzymes in isolated chloroplasts phenol oxidase in *Beta vulgaris*. *Plant Physiology, 24*, 1–15.

Bamisile, B. S., Akutse, K. S., Siddiqui, J. A., & Xu, Y. (2021). Model application of entomopathogenic fungi as alternatives to chemical pesticides: Prospects, challenges, and insights for next-generation sustainable

agriculture. *Frontiers in Plant Science*. https://doi.org/10.3389/fpls.2021.741804

Bates, L., Waldren, R. P., & Teare, I. D. (1973). Rapid determination of free proline for water stress studies. *Plant and Soil, 39*, 205–207.

Black, C. A., Evans, D. D., Ensminger, L. E., White, G. L., & Clark, F. E. (1981). *Methods of soil analysis. Part 2* (pp. 1–100). Agron. Inc.

Bray, H.G., & Thrope W. V. (1954): Analysis of phenolic compounds of interest metabolism. *Methods of Chemical Analysis,* 27–51.

Chowdhury, S., Bolan, N., Farrell, M., Sarkar, B., Sarker, J. R., Kirkham, M. B., ... & Kim, G. H. (2021). Role of cultural and nutrient management practices in carbon sequestration in agricultural soil. *Advances in agronomy, 166*, 131–196.

Czestkowski, W., Krzemiński, Ł, Piotrowicz, M. C., Mazur, M., Pluta, E., Andryianau, G., Koralewski, R., Matyszewski, K., Olejniczak, S., Kowalski, M., Lisiecka, K., Kozieł, R., Piwowar, K., Papiernik, D., Nowotny, M., Napiórkowska-Gromadzka, A., Nowak, E., Niedziałek, D., Wieczorek, G., … Bartoszewicz, A. (2024). Structure-based discovery of high-affinity small molecule ligands and development of tool probes to study the role of chitinase-3-like protein 1. *Journal of Medicinal Chemistry, 67*(5), 3959–3985.

Dass, A., Rajanna, G. A., Babu, S., Lal, S. K., Choudhary, A. K., Singh, R., Rathore, S. S., Kaur, R., Dhar, S., Singh, T., Raj, R., Shekhawat, K., Singh, C., & Kumar, B. (2022). Foliar application of macro-and micronutrients improves the productivity, economic returns, and resource-use efficiency of soybean in a semiarid climate. *Sustainability, 14*(10), Article 5825.

Devillers, P. (1988). "Prevsion du sucre melasse", Scurriesfrancases, Vol. 129, pp. 190–200. (C. F. The Sugar Beet Crop Book).

Dexter, S. T., Frakes, M. G., & Snyder, F. W. (1967). A rapid and practical method of determining extractable white sugar as may be applied to the evaluation of agronomic practices and grower deliveries in the sugar beet industry. *Journal of Sugar Beet Research, 14*, 433–454.

Dhaliwal, S. S., Sharma, V., Shukla, A. K., Verma, V., Kaur, M., Shivay, Y. S., ... & Hossain, A. (2022). Biofortification—A frontier novel approach to enrich micronutrients in field crops to encounter nutritional security. Molecules, 27(4), 1340.

Francis, D. V., Abdalla, A. K., Mahakham, W., Sarmah, A. K., & Ahmed, Z. F. (2024). Interaction of plants and metal nanoparticles: Exploring its molecular mechanisms for sustainable agriculture and crop improvement. *Environment International*. https://doi.org/10.1016/j.envint.2024.108859

Gomez, K. N., & Gomez, A. A. (1984). Statistical procedures for agricultural research. A Wiley-Inter-Sci. Publication. John Wiley and Sons, New York 2 th ed. 68p.

Hamzah Saleem, M., Usman, K., Rizwan, M., Al Jabri, H., & Alsafran, M. (2022). Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Frontiers in Plant Science, 13*, Article 1033092.

Hanwell, M. D., Curtis, D. E., Lonie, D. C., Vandermeersch, T., Zurek, E., & Hutchison, G. R. (2012). Avogadro: An advanced semantic chemical editor, visualization, and analysis platform. *Journal of Cheminformatics, 4*, 17. https://doi.org/10.1186/1758-2946-4-17

Jackson, M. L. (1973). *Soil chemical analysis* (Vol. 498, pp. 151–154). Prentice Hall of India Pvt. Ltd.

Jeong, C. H., & Shim, K. H. (2004). Quality characteristics of sponge cakes with addition of *Pleurotus eryngii* mushroom powders. *Journal of the Korean Society of Food Science and Nutrition, 33*, 716–722.

Kim, S., Chen, J., Cheng, T., Gindulyte, A., He, J., He, S., Li, Q., Shoemaker, B. A., Thiessen, P. A., Yu, B., Zaslavsky, L., Zhang, J., & Bolton, E. E. (2021). PubChem in 2021: New data content and improved web interfaces. *Nucleic Acids Research, 49*(D1), D1388–D1395. https://doi.org/10.1093/nar/gkaa971

Liu, X., Song, Q., Li, X., Chen, Y., Liu, C., Zhu, X., Liu, J., Granato, D., Wang, Y., & Huang, J. (2021). Effects of different dietary polyphenols on conformational changes and functional properties of protein–polyphenol covalent complexes. *Food Chemistry, 361*, Article 130071.

Liu, Y., Yang, X., Gan, J., Chen, S., Xiao, Z. X., & Cao, Y. (2022). CB-Dock2: Improved protein-ligand blind docking by integrating cavity detection, docking and homologous template fitting. *Nucleic Acids Research, 50*(W1), W159–W164. https://doi.org/10.1093/nar/gkac394

López-Gálvez, G., López-Alonso, M., Pechova, A., Mayo, B., Dierick, N., & Gropp, J. (2021). Alternatives to antibiotics and trace elements (copper and zinc) to improve gut health and zootechnical parameters in piglets: A review. *Animal Feed Science and Technology, 271*, Article 114727.

Mahmud, S., Mita, M. A., Biswas, S., Paul, G. K., Promi, M. M., Afrose, S., Hasan, R., Shimu, S. S., Zaman, S., Uddin, S., Tallei, T. E., Emran, T. B., & Saleh, A. (2021). Molecular docking and dynamics study to explore phytochemical ligand molecules against the main protease of SARS-CoV-2 from extensive phytochemical datasets. *Expert Review of Clinical Pharmacology, 14*(10), 1305–1315. https://doi.org/10.1080/17512433.2021.1959318

Makhlouf, B. S. I., Khalil, S. R. A. E., & Saudy, H. S. (2022). Efficacy of humic acids and chitosan for enhancing yield and sugar quality of sugar beet under moderate and severe drought. *Journal of Soil Science and Plant Nutrition, 22*(2), 1676–1691.

Maqbool, S., Hassan, M. A., Xia, X., York, L. M., Rasheed, A., & He, Z. (2022). Root system architecture in cereals: Progress, challenges, and perspective. *The Plant Journal, 110*(1), 23–42.

Maxwell, D. P., & Bateman, D. F. (1967). Changes in the activities of some oxidases in extracts of Rhizoctonia infected bean hypocotyle in relation to lesion maturation. *Phytopathology, 57*, 132–136.

Mekdad, A. A. A., & Shaaban, A. (2020). Integrative applications of nitrogen, zinc, and boron to nutrients-deficient soil improves sugar beet productivity and technological sugar contents under semi-arid conditions. *Journal of*

Plant Nutrition. https://doi.org/10.1080/01904167.2020.1757701

Misra, V., Sah, U., Mall, A. K., Kishor, R., & Pathak, A. D. (2017). Identification and evaluation of different sugar-beet germplasm for high yield and sucrose content under Indian agro-climatic conditions. *Bulletin of Environment, Pharmacology and Life Sciences, 6*(2), 292–295.

Misra, V., Lal, R. J., Mall, A. K., Srivastava, S., & Baitha, A. (2022). Integrated disease management in sugar beet for sustainable productivity. *Sugar beet cultivation, management and processing* (pp. 607–619). Springer Nature Singapore.

Morris, G. M., Huey, R., Lindstrom, W., Sanner, M. F., Belew, R. K., Goodsell, D. S., & Olson, A. J. (2009). AutoDock4 and AutoDockTools4: Automated docking with selective receptor flexibility. *Journal of Computational Chemistry, 30*(16), 2785–2791. https://doi.org/10.1002/jcc.21256

Mutale-Joan, C., Rachidi, F., Mohamed, H. A., Mernissi, N. E., Aasfar, A., Barakate, M., & Arroussi, H. E. (2021). Microalgae-cyanobacteria–based biostimulant effect on salinity tolerance mechanisms, nutrient uptake, and tomato plant growth under salt stress. *Journal of Applied Phycology, 33*, 3779–3795.

O'Boyle, N. M., Banck, M., James, C. A., Morley, C., Vandermeersch, T., & Hutchison, G. R. (2011). Open Babel: An open chemical toolbox. *Journal of Cheminformatics, 3*, 33. https://doi.org/10.1186/1758-2946-3-33

Pettersen, E. F., Goddard, T. D., Huang, C. C., Couch, G. S., Greenblatt, D. M., Meng, E. C., & Ferrin, T. E. (2004). UCSF chimera–a visualization system for exploratory research and analysis. *Journal of Computational Chemistry, 25*(13), 1605–1612. https://doi.org/10.1002/jcc.20084

Rappe, A. K., Casewit, C. J., Colwell, K. S., Goddard, W. A., III., & Skiff, W. M. (1992). UFF, a full periodic table force field for molecular mechanics and molecular dynamics simulations. *Journal of the American Chemical Society, 114*(25), 10024–10035. https://doi.org/10.1021/ja00051a040

Reddy, S. H., Al-kalbani, H., Al-Qalhati, S., Al-Kahtani, A. A., Al Hoqani, U., Azmi, S. N. H., & Settaluri, V. S. (2024). Proline and other physiological changes as an indicator of abiotic stress caused by heavy metal contamination. *Journal of King Saud University-Science, 36*(8), Article 103313.

Salama, N. H. H. (2021). Alternative control by natural compounds to powdery mildew disease on sugar beet with supporting investigation by scanning electron microscopy and X-ray. *Middle East Journal of Agriculture Research, 10*(2), 771–785. https://doi.org/10.36632/mejar/2021.10.2.51

Salarian, A. & Salari, A. (2020). Effect of foliar application of micronutrient fertilizers on the technological quality of sugar beet. *Journal of Sugar Beet*.

Sardans, J., & Peñuelas, J. (2021). Potassium control of plant functions: Ecological and agricultural implications. *Plants*. https://doi.org/10.3390/plants10020419

Sekaran, U., Lai, L., Ussiri, D. A., Kumar, S., & Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security–A review. Journal of Agriculture and Food Research, 5, 100190. sciencedirect.com

Sharma, R. K., Singh, V., Tiwari, N., Butcher, R. J., & Katiyar, D. (2020). Synthesis, antimicrobial and chitinase inhibitory activities of 3-amidocoumarins. *Bioorganic Chemistry, 98*, Article 103700.

Shib, A., Bhardwaj, G., Kumari, U., Singh, J., & Kaur, S. (2021). DeepSite: An ensemble-based deep learning approach for accurate and reliable prediction of protein binding sites. bioRxiv, 2021.03.08.434460. https://doi.org/10.1101/2021.03.08.434460

Snedecor, G. W., & Cochran, W. G. (1980). *Statistical Methods* (7th ed.). The Iowa State Univ. Press Amer.

Tamm, L., Thuerig, B., Apostolov, S., Blogg, H., Borgo, E., Corneo, P. E., Fittje, S., de Palma, M., Donko, A., Experton, C., Alcázar Marín, É., Morell Pérez, Á., Pertot, I., Rasmussen, A., Steinshamn, H., Vetemaa, A., Willer, H., & Herforth-Rahmé, J. (2022). Use of copper-based fungicides in organic agriculture in twelve European countries. *Agronomy, 12*(3), Article 673.

Tayyab, M., Wakeel, A., Mubarak, M. U., Artyszak, A., Ali, S., Hakki, E. E., & Ishfaq, M. (2023). Sugar beet cultivation in the tropics and subtropics: Challenges and opportunities. *Agronomy, 13*(5), Article 1213.

Tleuova, A. B., Wielogorska, E., Talluri, V. P., Štěpánek, F., Elliott, C. T., & Grigoriev, D. O. (2020). Recent advances and remaining barriers to producing novel formulations of fungicides for safe and sustainable agriculture. *Journal of Controlled Release, 326*, 468–481.

Umar, A. B., Uzairu, A., Shallangwa, G. A., et al. (2021). Ligand-based drug design and molecular docking simulation studies of some novel anticancer compounds on MALME-3M melanoma cell line. *Egyptian Journal of Medical Human Genetics, 22*, Article 6. https://doi.org/10.1186/s43042-020-00126-9

Wei, P., Zhao, F., Wang, Z., Wang, Q., Chai, X., Hou, G., & Meng, Q. (2022). Sesame (*Sesamum indicum* L.): A comprehensive review of nutritional value, phytochemical composition, health benefits, development of food, and industrial applications. *Nutrients, 14*(19), Article 4079.

Whitney, E. D., Lewellen, R. T., & Skoyen, I. O. (1983). Reaction of sugar beet to powdery mildew: Genetic variation, association among testing procedures, and results of resistance breeding. *Phytopathology, 73*, 182–185.

Yuan, P., Jiang, X., Wang, S., Shao, X., Yang, Q., & Qian, X. (2020). X-ray structure and molecular docking guided discovery of novel chitinase inhibitors with a scaffold of dipyridopyrimidine-3-carboxamide. *Journal of Agricultural and Food Chemistry, 68*(47), 13584–13593. https://doi.org/10.1021/acs.jafc.0c03742

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