

Effect of Fe^{2+} , Fe^{3+} , Ni^{2+} and Cr^{3+} ions on the growth and development of *Triticum aestivum* L

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Abstract

Background

Heavy metal contamination of agricultural soils in war-affected regions may reduce wheat productivity and threaten food security. At the same time, selected metal ions in chelated form may influence seed germination, plant growth, yield formation, and plant responses to bacterial infection. This study evaluated the effects of iron citrate, iron glycinate, and lysinate complexes of nickel and chromium on the growth and development of wheat plants and on their response to *Pseudomonas syringae*.

Results

Wheat plants were grown in pots for three months under controlled conditions and exposed to six treatments: untreated control, iron glycinate, iron citrate, nickel lysinate, chromium lysinate, and combined nickel plus chromium lysinates, each applied at 0.01 mg dm⁻³. Each treatment included non-infected and inoculated subgroups. Seed germination, stem length, grain number, and grain mass were assessed. Iron chelates did not show a clear effect on germination, stem length, or yield. In contrast, treatment with nickel and chromium lysinates increased seed germination to 90–97% and improved yield-related traits. Compared with the untreated control, nickel lysinate increased stem length by 13%, grain number by 72%, and total grain mass by 63%, whereas chromium lysinate increased grain number by 60% and total grain mass by 57.5%. Inoculation with *Pseudomonas syringae* caused transient leaf lesions, but plants recovered during cultivation. Infection had no clear effect on stem length and only a limited effect on mean grain weight.

Conclusions

At the tested dose, nickel and chromium lysinate complexes were associated with improved germination and yield performance of wheat, whereas iron citrate and iron glycinate showed little effect under the same conditions. Wheat plants were able to recover after inoculation with *Pseudomonas syringae* in the experimental system used. These findings suggest that low-dose nickel and chromium lysinate complexes may have stimulatory potential in wheat, although further validation under field conditions is required.

Background

Wheat (*Triticum aestivum* L.) is one of the most important agricultural crops worldwide, providing a major share of the caloric intake for a large part of the global population. Efficient wheat cultivation is closely linked to optimal growth conditions, in particular to soil composition and the availability of micro- and macroelements. Metals such as iron (Fe), nickel (Ni) and chromium (Cr) affect plant physiology: on the one hand, some of them are essential microelements for normal development, while on the other hand, at elevated concentrations they may exert toxic effects. During military operations, agricultural land is among the most heavily affected ecosystems. This is related not only to burnt military equipment left after active hostilities, but also to the accumulation of heavy metals in areas that have been subjected to intense shelling damage. The accumulation of heavy metals leads to contamination of fertile soils and, consequently, to reduced yield. At present, it is highly relevant to determine the ability of agricultural crops, in particular wheat, to germinate on such soils and to produce yields, as well as discovery of potential microbiological symbionts that would promote crop growth and development under elevated concentrations of heavy metal ions.

Iron is one of the fundamental elements for plants, as it is a component of cytochromes and respiratory and photosynthetic enzymes. Seed treatment with iron-containing salts (e.g. FeSO₄·7H₂O) increases germination percentage and promotes root and shoot growth in rice and other crops [1]. The use of α-Fe₂O₃ nanoparticles stimulates germination and growth of sunflower due to regulation of ROS signalling [2]. Similar effects are observed in wheat, where nanomagnetite increased biomass and enhanced the activity of antioxidant enzymes [3]. At the same time, excess iron or its nanoparticles can reduce root biomass, alter chloroplast structure and affect photosynthetic parameters [4].

Nickel functions as a cofactor of urease but becomes toxic at high concentrations. In sunflower seeds, Ni²⁺ ions at concentrations above 30–60 mg L⁻¹ inhibit germination and decrease the activity of α-amylase and protease [5]. In *Brassica napus*, Ni²⁺ caused a stronger decrease in germination than Co²⁺ [6]. A literature survey has shown that at concentrations above 100 μM nickel markedly reduces biomass and affects the pigment apparatus, while increasing H₂O₂ and thiol levels [7]. Some aquatic plant species are more tolerant to the effects of nickel ions [8]. In a study [9] it was demonstrated that NiO nanoparticles at low concentrations stimulate photosynthesis and biomass accumulation in wheat.

Cr³⁺ is not an essential element for plants and predominantly exhibits toxic effects. A concentration of chromium(III) above 50 ppm inhibits germination and growth of millet (*Pennisetum glaucum*) [10]. In alfalfa, 40 ppm Cr reduces germination by 54%, whereas in wheat even 10 mg L⁻¹ causes 80% growth inhibition [11]. In legume crops, Cr³⁺ suppresses root and coleoptile growth and reduces leaf area and biomass [12]. At the biochemical level, Cr³⁺ induces the formation of reactive oxygen species, damaging membranes and enzyme systems [13].

Another persistent problem in agriculture is diseases of crop plants, which lead to reduced yields or even complete crop failure. The phytopathogenic bacterium *Pseudomonas syringae* is one of the most widespread causal agents of plant diseases, infecting a broad range of crops, including tomato, wheat and legumes [14]. To cause disease, the bacterium enters the plant through wounds or natural openings such as stomata and multiplies in the

apoplast. *P. syringae* also serves as a powerful model for understanding the mechanisms of bacterial virulence and pathogen adaptation to the host, as well as microbial evolution, ecology and epidemiology. Its attack mechanism involves various virulence factors: effector proteins translocated into plant cells via the type III secretion system (T3SS), low-molecular-weight toxins, exopolysaccharides, cell wall-degrading enzymes and plant hormones (or hormone mimics).

The effectiveness of plant defence against infection is determined not only by plant immune mechanisms but also by the availability of microelements in the soil, among which nickel (Ni^{2+}), chromium (Cr^{3+}) and iron ($\text{Fe}^{2+}/\text{Fe}^{3+}$) ions play a particularly important role. These elements can modify the physiological and biochemical status of plants and indirectly influence the development of the infection process.

Iron is a key microelement in the plant–pathogen system, as it participates in photosynthesis, respiration and the synthesis of reactive oxygen species (ROS), which are important components of the immune response [15]. Limiting the availability of Fe^{3+} to the pathogen via plant siderophore synthesis or competition for iron is one of the main mechanisms restraining the growth of *P. syringae* [16]. Studies show that excess Fe^{2+} can enhance oxidative stress in bacterial cells, whereas an optimal level promotes the activation of defence enzymes in plants [17].

Nickel (Ni^{2+}) at moderately elevated concentrations can stimulate ROS formation and enhance the hypersensitive response of plants against *P. syringae* [18]. It is known that Ni^{2+} can affect the expression of genes encoding defence proteins and modulate the synthesis of phenolic compounds involved in the formation of barriers against bacterial infection [18].

Elevated concentrations of Cr^{3+} lead to oxidative stress and membrane damage; however, within microdose ranges it may promote the induction of defence enzymes—peroxidases and catalase—that participate in the formation of nonspecific immunity against *Pseudomonas* [19]. In addition, Cr^{3+} can alter the bioavailability of other microelements, particularly iron, which indirectly affects the intensity of pathogen growth.

Thus, the effects of Ni^{2+} , Cr^{3+} and $\text{Fe}^{2+}/\text{Fe}^{3+}$ ions on plant resistance to *Pseudomonas syringae* infection are dual in nature: on the one hand, they can enhance immune mechanisms and antioxidant protection, while on the other hand, at high concentrations they cause toxicity and decreased plant tolerance. This indicates the need for further studies on the optimal concentrations and interactions of these elements in the plant–pathogen system.

Chelated forms of Fe (especially Fe-DTPA and Fe-glycinate) provide higher iron bioavailability, stability in soil and resistance to oxidation, thereby reducing the risk of toxicity. FeSO_4 is effective only in the short term, whereas Fe-EDTA and Fe-DTPA maintain uniform plant nutrition over an extended period. Fe-glycinate is a bioorganic form that combines high uptake efficiency with the absence of toxic effects. However, an excess of even chelated forms (above 100–150 μM) can induce oxidative stress [4, 20–22].

However, the specific effects of these ions at different concentrations on the growth and development of wheat require further investigation. The aim of this study was to assess the influence of $\text{Fe}^{2+}/\text{Fe}^{3+}$, Ni^{2+} and Cr^{3+} ions on seed germination, morphological parameters and biomass of wheat plants, as well as on plant defence against the bacterium *Pseudomonas syringae*.

Methods

Plants of *Triticum L.* were grown in vivo in pots using a universal potting soil mixture (TM Floriada brand) at room temperature (20–25°C) under natural light. Wheat seeds, pre-sterilized, were sown in long plastic containers (40 × 14.7 × 18.7 cm) in groups of 30 seeds. Each container was filled with 5 dm³ of soil.

The plants were divided, depending on the metal or metal mixture, into experimental groups that received the corresponding treatments in the soil during cultivation:

- 1 (control) – cultivation without addition of metal-containing solutions
- 2 – cultivation in a soil mixture with the addition of 50 cm³ of an iron(II) glycinate solution at a concentration of 0.01 mg dm⁻³,
- 3 – cultivation in a soil mixture with the addition of 50 cm³ of an iron(III) citrate solution at a concentration of 0.01 mg dm⁻³,
- 4 – cultivation in a soil mixture with the addition of 50 cm³ of a nickel(II) lysinate solution at a concentration of 0.01 mg dm⁻³ and with preliminary seed treatment by this solution before sowing,
- 5 – cultivation in a soil mixture with the addition of 50 cm³ of a chromium(III) lysinate solution at a concentration of 0.01 mg dm⁻³ and with preliminary seed treatment by this solution before sowing,
- 6 – cultivation in a soil mixture with the addition of 50 cm³ of a solution of nickel and chromium lysinates at a concentration of 0.01 mg dm⁻³.

Cultivation was carried out under uniform illumination with a 16-hour photoperiod (8-hour darkness) at an ambient temperature of 23 ± 2°C. Irrigation with metal-containing solutions in a volume of 50 cm³ was performed three times at 30-day intervals during the three-month cultivation period. Morphological characteristics of the plants were assessed at the stage of inflorescence formation. Shoot length, seed weight and seed number were measured.

The *Pseudomonas syringae* culture was provided by the Department of Molecular Genetics, Institute of Cell Biology and Genetic Engineering, National Academy of Sciences of Ukraine, Kyiv.

During the cultivation period, plants were inoculated twice with *Pseudomonas syringae*. For this purpose, plants from each experimental group were divided equally into control (C) and infected (I) subgroups: the infected plants were injected with a bacterial suspension into the stem, whereas the control plants received injections of sterile buffer only.

Results

Morphological analysis of *Triticum* L. plants grown in vivo

Plants were grown for three months. Ten plants from each group were selected for analysis. Mean seed germination results under different treatment conditions are shown in Fig. 1. Morphological parameters of the plants are presented in Tables 1 and 2.

Figure 1 – Wheat seed germination

- 1 – control group;
- 2 – group grown with iron glycinate;
- 3 – group grown with iron citrate;
- 4 – group grown with nickel;
- 5 – group grown with chromium;
- 6 – group grown with nickel and chromium;
- 7 – initial number of seeds for all groups.

Table 1
– Stem length in the experimental groups

Sample no.	Mean stem length, cm	Difference in length compared with control, %
1	53.7 ± 2.1	-
2	52.0 ± 1.9	-3.17
3	55.0 ± 3.8	2.42
4	60.7 ± 2.0	13.04
5	53.5 ± 0.5	-0.37
6	62.2 ± 2.2	15.83

Table 2
– Grain yield in the experimental groups

Sample	Total number of grains in the experimental group	Difference in total number of grains between the group and the control, %	Grain weight in the sample, g	Difference in grain weight compared with control, %
1	99	-	1.813	-
2	141	42.0	2.605	44.00
3	122	23.0	1.942	7.11
4	170	72.0	2.963	63.43
5	158	60.0	2.855	57.47
6	116	18.0	2.645	45.89

Inoculation of plants with *Pseudomonas syringae* was carried out twice, 28 days after germination. Disease symptoms were observed 14 days later (Fig. 2). Assessment of the morphological parameters of plants from the control and infected groups was performed at the end of the experiment at the spike formation stage (Table 3).

Figure 2 – Leaf symptoms and recovery of *Triticum aestivum* L. plants after inoculation with *Pseudomonas syringae*.

Table 3
Morphological parameters of wheat plants in control and infected groups

Parameter	Control group		Group 2		Group 3		Group 4		Group 5		Group 6	
	Control	Infected	Control	Infected	Control	Infected	Control	Infected	Control	Infected	Control	Infected
Mean grain weight, $\times 10^{-2}$ g	3.2 $\pm$ 0.3	3.4 $\pm$ 0.4	3.4 $\pm$ 0.5	1.5 $\pm$ 0.6	3.1 $\pm$ 0.4	3.4 $\pm$ 0.1	1.4 $\pm$ 0.5	2.9 $\pm$ 0.5	1.5 $\pm$ 0.3	2.5 $\pm$ 0.4	1.2 $\pm$ 0.3	2.2 $\pm$ 0.6
Stem length, cm	55.5 $\pm$ 4	58.5 $\pm$ 3	54 $\pm$ 4	53 $\pm$ 3	51 $\pm$ 7	62 $\pm$ 4	54 $\pm$ 4	58 $\pm$ 1	55 $\pm$ 2	56 $\pm$ 2	60 $\pm$ 3	64 $\pm$ 4

Values are presented as mean $\pm$ SD (n = 10). SD, standard deviation.

Discussion

Seed germination in soil was not uniform. Germination in groups 1, 2, 3 and 6 ranged between 46 and 66%, in contrast to groups 4 and 5, which were pre-treated with solutions of nickel and chromium lysinate complex salts, where seed germination reached 90% and 97%, respectively. This effect can be associated with the positive action of nickel (Ni^{2+}) and chromium (Cr^{3+}) complexes at low concentrations (0.01 mg dm^{-3}). Nickel is required for the functioning of the enzyme urease, which is involved in the conversion of urea into ammonia and CO_2 , promotes nitrogen metabolism and the initial stages of germination. At elevated concentrations ($> 1 \text{ mg dm}^{-3}$), nickel exerts a toxic effect on seeds and seedlings of plants:

- it suppresses energy metabolism in seed cells;
- it reduces the rate of germination and root elongation;
- it damages membranes and causes the accumulation of reactive oxygen species (ROS) and oxidative stress;
- it may lead to mutagenic changes in DNA [23].

In turn, chromium(III) ions in small amounts may participate in carbohydrate and protein metabolism, but their role in plants is limited and not critical.

Comparison of the effects of nickel and chromium (Table 4) indicates the potential of using microconcentrations of nickel to stimulate plant growth and development.

Table 4
– Effects of nickel (Ni^{2+}) and chromium (Cr^{3+}) ions on seed germination.

Effect parameter	Nickel ions (Ni^{2+})	Chromium ions (Cr^{3+})
Biological role at low doses ($0.01\text{--}0.5 \text{ mg dm}^{-3}$)	Essential microelement for plants: urease cofactor; Ni deficiency disrupts nitrogen metabolism and growth [8, 6]	No specific essential role in germination has been established; in plants Cr is mostly regarded as a toxicant [24].
Seed germination	Excess Ni inhibits germination; NiCl_2 most strongly reduces germination and root growth (up to severe inhibition at 500 mg/dm^3) [23].	With increasing Cr^{3+} concentration ($5\text{--}10 \text{ mg dm}^{-3}$), germination decreases; this has been demonstrated in <i>Nigella</i> /tomato/citrus as early-development models [25].
Root and shoot growth	High doses of Ni^{2+} reduce root and shoot length; growth inhibition of seedlings in legumes and cereals has been reported [23].	Cr^{3+} damages roots and reduces seedling growth; decreases in biomass and root length have been recorded [24].
Nutritional/metabolic effects	Adequate microdoses of Ni enhance urease activity and may improve initial nitrogen metabolism [26].	For Cr^{3+} , disturbances of photosynthetic and respiratory processes are noted at early developmental stages [24].
Genetic effects / toxicity	Excess Ni causes accumulation of ROS and membrane damage, which inhibits germination [18].	Cr^{3+} induces ROS stress (elevated H_2O_2 /MDA), reducing seedling viability [27].
Safety range	Very narrow: from a microfertilizer effect to toxicity as concentration increases (depending on the salt and plant species) [8, 23]	Less toxic than Cr^{6+} , but at elevated doses it also markedly inhibits germination and early growth [25].
Applied observations/agronomy	Seed treatment/fertilization with Ni microdoses may be beneficial (depending on crop and form of application) [28, 29].	To reduce Cr-induced damage, protectants/priming treatments are selected; Cr^{3+} itself is not used as a fertilizer [30].
In contrast to nickel (Ni^{2+}) and chromium (Cr^{3+}) ions, iron compounds have a positive effect on seeds and plants, but this depends on the iron form and its bioavailability to cells (Table 5). Iron citrate (Fe^{3+} –citrate) is a well-soluble iron form that is readily transported in solutions and is used as a chelated form in plant nutrition [31–33]. Its effects on seed germination are as follows:		

- at low concentrations it stimulates germination by providing seeds with available iron for initial metabolic processes;

- it improves seedling respiration, since citrate participates in the Krebs cycle, enhancing cellular energy supply.

However, excess iron may cause a toxic effect (oxidative stress via Fenton reactions) and at high doses can inhibit growth due to: accumulation of reactive oxygen species (ROS); oxidative damage to proteins and membranes; changes in medium pH, since citrate is a weak acid [34].

Iron glycinate ($\text{Fe}^{2+}/\text{Fe}^{3+}$ –glycinate) has higher cellular bioavailability than inorganic iron salts and gently penetrates through cell membranes due to amino acid transport. It also promotes faster formation of root hairs and seedling growth at physiological concentrations. Glycine in the complex partially protects cells from free-radical reactions and is less toxic in excess. At high doses it can also induce oxidative stress, but its effects are milder than those of citrate or sulfate [35].

Table 5
– Effects of Fe^{3+} citrate and $\text{Fe}^{2+}/\text{Fe}^{3+}$ glycinate on seed germination.

Characteristic	Fe^{3+} citrate	$\text{Fe}^{2+}/\text{Fe}^{3+}$ glycinate
Type of chelate	Organic acid (citrate)	Amino acid chelate (glycinate)
Bioavailability	Stable Fe binding; well mobilized in the plant with citrate acting as a complexing agent [35].	High bioavailability due to the amino acid glycine, which facilitates uptake and protects against Fenton reactions [36].
Effect on germination	Promotes iron uptake, activates respiratory and enzymatic metabolism; excess may cause oxidative stress (free radicals)—overall trend consistent with the citrate-chelation mechanism [23, 32].	Increases the activity of antioxidant enzymes (catalase, peroxidase) and improves overall plant status under Fe deficiency—experiment in blackgram [36].
Antioxidant protection	Excess Fe^{3+} citrate concentration has been shown to cause oxidative stress [36].	Application of $\text{Fe}^{2+}/\text{Fe}^{3+}$ glycinate increases catalase and peroxidase activity [36].
General conclusion	Effective Fe source, especially during seed germination, but requires dose control because of the risk of oxidative damage [36].	Consistently supports germination and is safer with respect to oxidative stress, especially in biotic or agronomic tests [36].

The difference in mean shoot length between the control and treated groups lay within the margin of error. All plants had shoot lengths ranging from 53 to 62 cm.

It is also worth noting that although iron is more important and beneficial for plants, the effect of Ni^{2+} and Cr^{3+} lysinates proved to be more pronounced with respect to grain formation in the studied plants. Plants of group 4, to which a nickel lysinate solution at a concentration of 0.01 mg dm^{-3} was added during growth, had a 72% higher grain number and a 63% higher total grain mass compared with the control. Plants of group 5, to which a chromium lysinate solution at a concentration of 0.01 mg dm^{-3} was added during growth, showed increases of 60% and 57.5%, respectively. This result can be explained by the positive effect of micro concentrations of heavy-metal complexes on plant physiology.

Disease symptoms in the different experimental groups caused by the bacterium *Pseudomonas syringae* were observed between days 12 and 14 after inoculation (Fig. 2). Each infected plant exhibited characteristic ruptures in the leaf blade with translucent margins. During the subsequent 14 days, complete regeneration of the affected leaves occurred in the infected wheat plants. This may be related to the intrinsic resistance of the plant to the bacterium. In resistant cultivars, a hypersensitive response (HR) is activated—local cell death at the site of bacterial entry. This limits the spread of infection, and the plant can recover by producing new healthy shoots and leaves [37]. The site of infection localization is also important. For example, if only the leaves are affected, after their death the plant is able to compensate for the loss by producing new leaves. In contrast, if the bacterium penetrates the vascular system or generative organs, recovery is much poorer or impossible [38].

Alongside internal mechanisms of self-defence and plant regeneration, the environment plays a major role. Under favorable conditions (adequate light, optimal temperature, and the presence of microelements such as $\text{Fe}^{2+}/\text{Fe}^{3+}$, Zn^{2+} , Mn^{2+}), plants more effectively restore antioxidant protection and seal damaged tissues. Under conditions of high humidity and low temperature, the spread of *P. syringae* is more active and the recovery process is impeded [37–41]. In a study [38] it was found that in tomato (*Solanum lycopersicum*), following primary infection with *P. syringae* pv. *tomato*, the formation of systemic acquired resistance (SAR) is sometimes observed, which increases resistance to reinfection. In wheat and barley, local lesions can heal, but severe infection reduces yield [41].

The effect of wheat infection by *P. syringae* on shoot height falls within the range of statistical error when compared with the control. The same applies to the mean grain weight in the control and in group 3. In group 2, however, the mean grain weight was higher in the control than in the infected plants, which is essentially an expected result. Yield reduction may occur due to damage to the leaf surface by *P. syringae*, because necrotic spots and water-soaked lesions form on the leaves, reducing photosynthetic activity; consequently, fewer assimilates are transported to the spike, directly decreasing grain mass [41]. This may also result from disruption of water balance, since the pathogen, through effector proteins (such as Hop and Avr types), causes imbalance in stomatal regulation, thereby reducing the plant's ability to use water efficiently. As a consequence, a decrease in turgor and slower grain filling are observed [41]. Infection also accelerates tissue senescence (via activation of reactive oxygen species and hormonal changes), shortening the grain-filling period. As a result, the grain formed is smaller and lighter. In addition, energy expenditure on defence responses—activation of systemic acquired resistance (SAR) and local immune responses—also affects grain mass [41].

Groups 4, 5 and 6 show contradictory data, since the mean grain weight in infected plants is 50% higher than the mean grain weight in healthy plants, although these values lie within the normal range for wheat grain mass (1000 grains weighing from 25 to 55 g). Ni^{2+} and Cr^{3+} ions separately had a positive effect on wheat yield in both infected and non-infected plants, increasing grain number and total grain mass by 70% and 60%, respectively. It is likely that this effect was caused by the complex salts of heavy-metal ions that were added to the soil during wheat growth and development, but this requires further investigation.

Winter wheat cultivars normally have stem heights ranging from 0.5 to 1.2 m. The obtained data on stem height in the experimental groups indicate that metal ions and the bacterium *P. syringae* do not have a statistically significant effect.

Strengths and limitations

A strength of this study is the parallel comparison of infected and non-infected wheat groups under controlled experimental conditions. At the same time, several limitations should be acknowledged. The experiment was performed under pot conditions rather than in the field, which limits direct agronomic extrapolation. In addition, the study focused on morphological endpoints and did not include biochemical or molecular markers of plant response. Finally, broader validation across cultivars, doses, and environmental conditions is still required.

Conclusions

It was determined that treatment of grain with Ni^{2+} and Cr^{3+} lysinates and their addition during the growth and development of wheat plants affect seed germination and plant yield. Addition of Ni^{2+} lysinate at a concentration of 0.01 mg dm^{-3} promoted seed germination, increased shoot length by 13%, grain number by 72% and total grain mass by 63% compared with the control. Addition of Cr^{3+} lysinate at a concentration of 0.01 mg dm^{-3} increased seed germination up to 97%, grain number by 60% and grain mass by 57.5% compared with the control.

Seed treatment and incorporation into the soil mixture of Fe^{3+} citrate and $\text{Fe}^{2+}/\text{Fe}^{3+}$ glycinate solutions did not affect wheat growth (germination, stem length, grain number or total grain mass).

It was established that wheat shoots can recover after infection with *Pseudomonas syringae* if the infection is contained by immune responses (hypersensitive response, SAR). In the case of severe infection, when the pathogen spreads systemically, recovery is incomplete and is accompanied by reduced growth and yield.

Declarations

Ethics approval and consent to participate:

Not applicable.

Consent for publication:

Not applicable.

Availability of data and materials:

All data generated or analysed during this study are included in this published article and its supplementary information files.

Competing interests:

The authors declare that they have no competing interests.

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Authors' contributions

HNB: Supervision, project administration, methodology, resources, and review of the experimental design.

DIV: Investigation, formal analysis, data curation, visualization, and writing of the original draft.

DY: Methodology, validation, participation in data interpretation, and manuscript review and editing.

KNV: Writing – review and editing, language editing, and English translation of the manuscript.

All authors read and approved the final manuscript.

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Figures

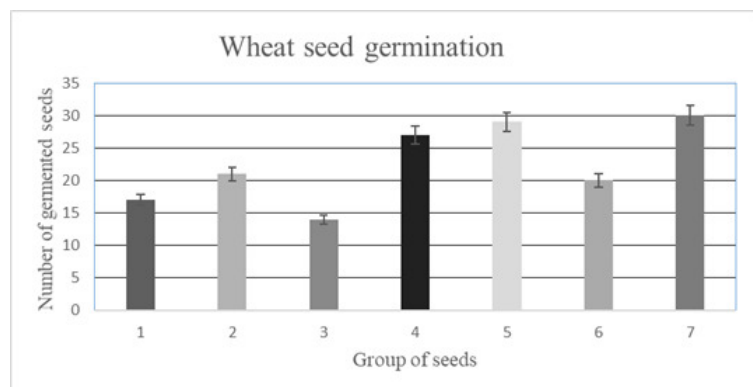


Figure 1

Wheat seed germination

- 1 – control group;
- 2 – group grown with iron glycinate;
- 3 – group grown with iron citrate;
- 4 – group grown with nickel;
- 5 – group grown with chromium;
- 6 – group grown with nickel and chromium;
- 7 – initial number of seeds for all groups.

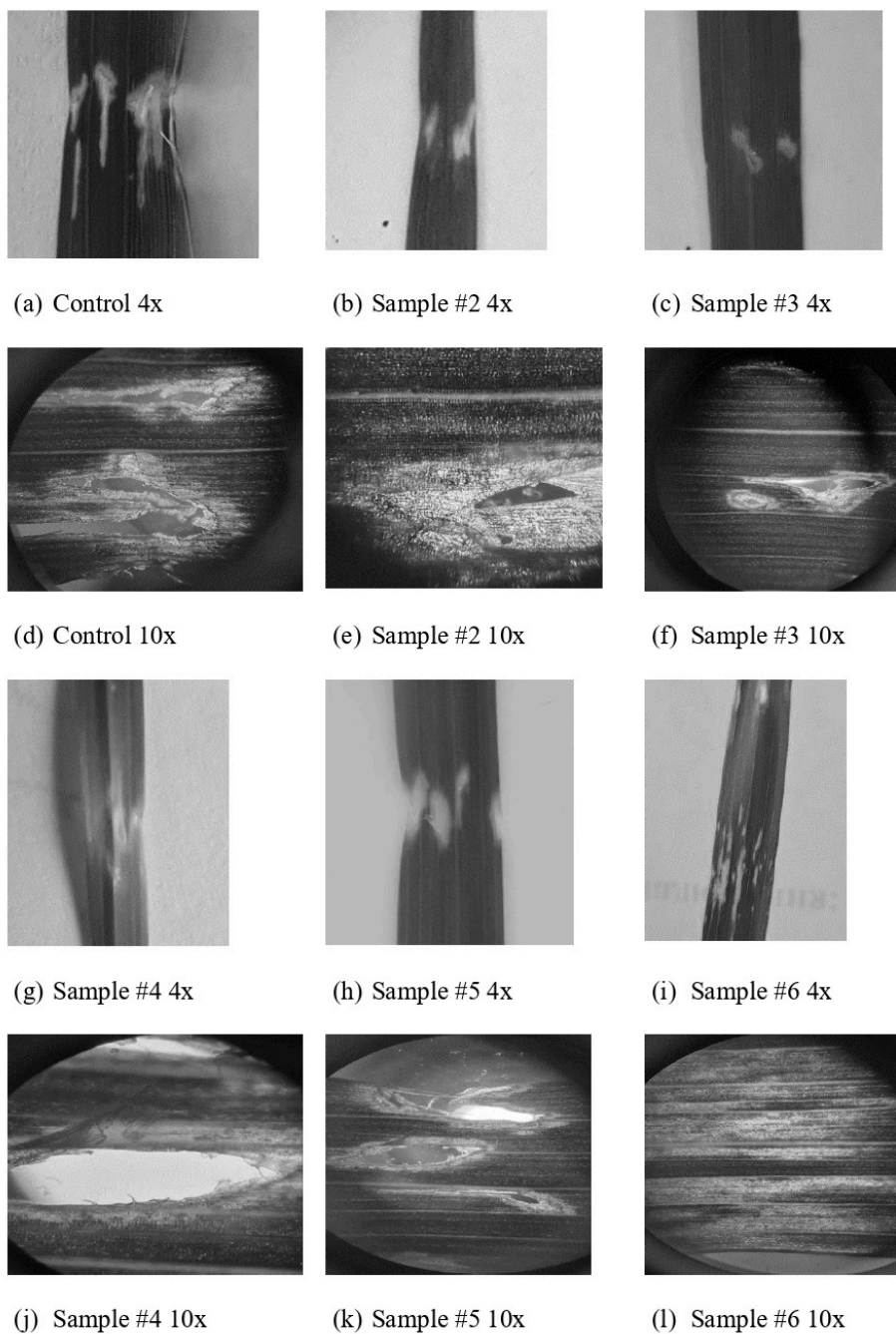


Figure 2

Leaf symptoms and recovery of *Triticum aestivum*L. plants after inoculation with *Pseudomonas syringae*.