

Non-competitive and competitive sorption of imidacloprid and KNO_3 onto soils and their effects on the germination of wheat plants (*Triticum aestivum* L.)

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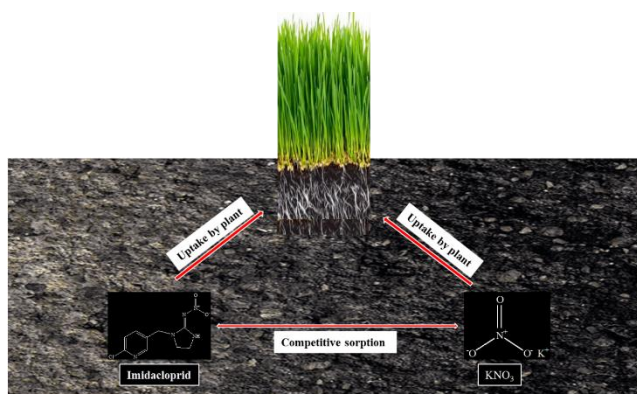
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Graphical abstract



Abstract

The non-competitive and competitive adsorption/desorption of agrochemicals into soil play an important role in the fate and behaviour of contaminants in the environment. Non-competitive and competitive adsorption/desorption experiments of imidacloprid and KNO_3 into alluvial soil and sandy soil were performed via batch experiments. Non-competitive and competitive experiments showed that imidacloprid was strongly more adsorbed and desorbed than KNO_3 in both tested soils. The adsorption of imidacloprid and KNO_3 was greater in the non-competitive experiments than in the competitive experiments, as their presence together reduced the chances of association with the adsorption sites onto soil for each of them individually. The adsorption and desorption of imidacloprid were greater than those of KNO_3 in the two soil types. Imidacloprid adsorption was greater in the sandy soil than alluvial soil, while KNO_3 was greater in the alluvial soil than sandy soil. The best fits were obtained with the Langmuir model in both soils for competitive and non-competitive adsorption, and competitive and non-competitive desorption. The data showed a reduction in the relative root and shoot

elongation percentage for wheat plants when imidacloprid was combined with KNO_3 or with imidacloprid alone. On the other hand, the use of KNO_3 fertilizer alone resulted in a significant increase in root and shoot length.

Keywords: Sorption, imidacloprid, KNO_3 , soil, germination, wheat plant

1. Introduction

Wheat is the most significant grain crop, providing 40% of the world's energy calories and 20% of the protein supply (Hussain *et al.* 2022). It is a key staple crop because it feeds 35% of the world's population (Ahmed *et al.* 2013; Hussain *et al.* 2022). Many insect pests associated with wheat crops, such as aphids, wheat midges, termites, and soil pests, infest and cause damage, resulting in significant output losses (Zhang *et al.* 2016; Fouad 2023a; Zhang *et al.* 2016). Termite infestation in wheat crops begins with sowing and continues until harvest, and poor germination may occur as a result of termite damage. Imidacloprid pesticide is used to combat these pests, and to treat seeds before planting to prevent soil insects from damaging seeds (Ko *et al.* 2014). The availability of nutrients in soil can be enhanced by using fertilizers such as KNO_3 , resulting in maximum wheat yield (Hussain *et al.* 2022).

Indeed, agricultural sustainability has long been associated with the use of a wide variety of pesticides that control disease-causing pests and crop-destroying insects (Tariq *et al.* 2016) and the use of fertilizers to increase vegetative growth. As an outcome, large amount of agrochemicals, such as imidacloprid and KNO_3 , enter soils via soil treatments, seed treatments, spray drifts, or wash-off from treated foliage (Tariq *et al.* 2016). These agrochemical residues may be evaporated directly with evaporating soil moisture and/or leached into groundwater and surface waters by leaching or run-off from the soil (Fouad 2023b). Soil is the primary reservoir

of agrochemicals in terrestrial systems. Increased agrochemical concentrations in soil can have unfavourable impacts, such as phytotoxicity, decreased agricultural production, and bioaccumulation (Soria *et al.* 2020).

Agrochemicals, which include pesticides and fertilizers, are the most dangerous agricultural soil contaminants (Tariq *et al.* 2016; El-Aswad *et al.* 2023a). The problem is compounded if the soil has a mixture of pesticides and fertilizers, as this makes the remediation procedure more complex. The degradation of agrochemicals is an essential process that contributes to the removal of contaminated soils and bodies of water (Fouad *et al.* 2023a, 2023b). Pesticide-fertilizer complexation interactions may lower the rate of pesticide degradation into soil (Tariq *et al.* 2016; El-Aswad *et al.* 2024a, 2024b), and increase adsorption onto soil components. Understanding the behaviour of agrochemicals in soils is aided by a number of characteristics, such as the organic matter content, moisture content, pH, soil texture, and soil mineral content (Tariq *et al.* 2016). The ionic composition of a natural field's soil solution is a mixture of cations and diverse anions. As a result, an evaluation of agrochemical sorption is required to apply laboratory results to field circumstances (Kamewada 1996).

Sorption/desorption is one of the most important processes influencing the fate and distribution of agrochemicals in the soil/water ecosystem. It is usually used to describe the process of pesticide partitioning between a water solution and soil (Fouad *et al.* 2024a, 2024b). Sorption also impacts agrochemical availability in soil solutions, which governs the amount of imidacloprid and KNO_3 accessible for uptake by wheat plants. The features of the soil, as well as its competitive behavior for adsorption sites, influence agrochemical adsorption (Soria *et al.* 2020). It is still unclear what factors influence the binding affinity and interactions of imidacloprid and KNO_3

in the complex soil environments. Therefore, this research aimed to study the interaction between imidacloprid and KNO_3 fertilizer in two different soils and to understand the mechanism of their absorption and desorption, as well as their impact on the germination rate of wheat seeds.

2. Materials and methods

2.1. Agrochemicals

Imidacloprid (N-1-6-chloro-3-pyridyl-methyl-4,5-dihydroimidazol-2-yl-nitramide), CAS-number (138261-41-3), technical grade (97%), chemical structure (Figure 1), and appearance (colourless crystals); was obtained from KZ Pesticides and Chemicals Company, Egypt.

KNO_3 (potassium nitrate), CAS-Number (7757-79-1), technical grade (99%), chemical structure (Figure 1), and appearance (white solid); was obtained from the El-Gomhouria Chemical Company, Egypt.

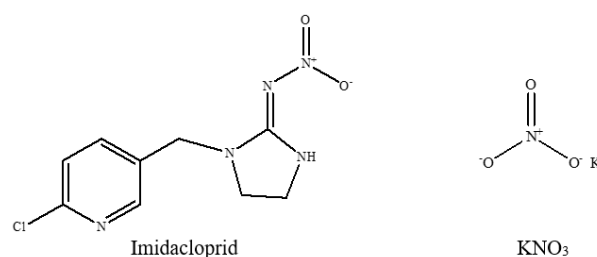


Figure 1. Chemical structures of imidacloprid and KNO_3 .

2.2. Soil and site characteristics

Soil samples were analysed for various physicochemical characteristics that are considered important for the adsorption and desorption of agrochemicals. The site and characteristics of the tested soils are presented in Table (1). Particle size analysis, pH, EC, organic matter (OM), total carbonate content, water holding capacity (WHC), and cation and anion contents are among these factors (Day and Black 1965; Abdel-Raheem *et al.* 2023).

Table 1. Physicochemical properties of the tested soils

| Characteristics | Alluvial soil | Sandy soil |
|--------------------------------|-----------------|----------------|
| Coordinates (N/E) | 304835/31151472 | 173085/3367732 |
| Texture | Clay | Sand |
| pH | 8.22 | 7.40 |
| EC (ds/m) | 2.06 | 9.50 |
| WHC (%) | 40 | 35 |
| OM (%) | 1.26 | 0.16 |
| Total carbonate (%) | 15.97 | 3.76 |
| Cations (meq/L) | | |
| Ca ⁺⁺ | 4.01 | 32.00 |
| Mg ⁺⁺ | 3.20 | 15.00 |
| Na ⁺ | 18.10 | 64.90 |
| K ⁺ | 0.41 | 2.25 |
| Anions (meq/L) | | |
| CO ₃ ⁻ | 0.41 | 0.00 |
| H CO ₃ ⁻ | 1.50 | 4.50 |
| Cl ⁻ | 16.92 | 100.00 |

2.3. Adsorption isotherm

The non-competitive and competitive adsorption/desorption of imidacloprid and KNO_3 at room

temperature was studied in a batch equilibrium system according to El-Aswad *et al.* (2023b). Initially, agrochemical solutions with concentrations in the 0-20 µg/mL range were prepared in ethanol and then mixed with a CaCl₂ (0.01 Molar) solution. Soil samples (1g) were weighed into glass tubes containing imidacloprid and KNO₃ and adjusted with CaCl₂ solution to reach the appropriate ratio (1:5). The agrochemicals were added to reach imidacloprid and KNO₃ concentrations equivalent to 0, 6.25, 12.5, 25, 50, 75, and 100 µg/g soil. The samples were shaken for 24 hours (140 revolutions/minute) before being centrifuged for 7 minutes (5000 rpm). The concentration of imidacloprid in the supernatant was then determined using a UV spectrophotometer (Fouad 2022), and the concentration of KNO₃ was determined using a flame photometer (Heidari *et al.* 2014). The amount of imidacloprid and KNO₃ retained by the adsorbent was determined based on the difference in agrochemical concentration between the initial and final equilibrium solutions. For the binary mixture adsorption isotherms, each individual concentration of imidacloprid and KNO₃ described above was collected and blended together to determine the concentration of the mixture of imidacloprid + KNO₃. The concentrations were then blended with soil for a competitive adsorption test.

2.4. Desorption isotherm

Desorption studies were carried out immediately following adsorption experiments using a parallel setup for all concentrations. Following the adsorption isotherm experiment, 5 mL of CaCl₂ (0.01 Molar) solution was added to each tube for the desorption isotherm equilibrium stage using a decant refill procedure. For 24 hours, the tubes were mechanically shaken at 140 rpm to establish a fresh desorption equilibrium. The liquid phase containing the desorbed agrochemicals was analysed after centrifugation. The amount of agrochemicals desorbed in the centrifuge sediment was compensated for the amount in the solution left with the soil by taking the final concentration of the solution and the weight of the retained solution into account (Fouad *et al.* 2024c, 2024d).

2.5. Langmuir isotherm model

The Langmuir model assumes homogeneous adsorption energies on the surface and no adsorbate transmigration in the plane of the adsorbent surface. The Langmuir equation can be written as follows:

$$\frac{1}{q_e} = \frac{1}{bq_m} \frac{1}{C_e} + \frac{1}{q_m}$$

where q_e is the amount of solute adsorbed per unit weight of adsorbent (µg/g), C_e is the solute's equilibrium concentration in the bulk solution (mg/L), q_m is the maximum adsorption capacity (µg/g) and b is a constant related to the free energy for adsorption (L/mg) (El-Aswad *et al.* 2023a).

2.6. Seed germination assay

We used; a Phytotoxkit germination assay to estimate the phytotoxic effects of imidacloprid and potassium nitrate

(Phytotoxkit 2004), either/individually or in combination, at different concentrations of 0, 6.25, 12.5, 25, 50, 75, and 100 µg/g soil. Two types of soil clay and sandy soil were used. Flat, transparent test plates; were filled with equal weights of moist clay and/or sandy soil (saturated soil with WHC). Ten wheat seeds (*Triticum aestivum* L.) were placed at equal distances near the middle edge of the test plate on filter paper placed over moist alluvial or sandy soil. The test plates were closed with transparent covers, placed vertically in a rack and incubated in an incubator for 6 days in the dark at 25±2 °C. Following the incubation, the root and shoot length, germination percentage, relative elongation (%), relative germination rate, and germination index were calculated according to AOSA (1978); as follows:

Relative germination rate =

$$\frac{(\text{Seeds germinated in test sample} \times 100)}{\text{Seeds germinated in control}}$$

Relative root elongation =

$$\frac{(\text{Mean root length in test sample} \times 100)}{\text{Mean root length in control}}$$

Germination Index =

$$\frac{(\text{Relative germination rate} \times \text{Relative root elongation})}{100}$$

2.7. Statistical analysis

The results of adsorption/desorption were analysed to obtain standard errors and R-squared values using Microsoft Excel 2019, while the germination data were statistically analysed using a one-way ANOVA with SPSS software (Fouad 2023c).

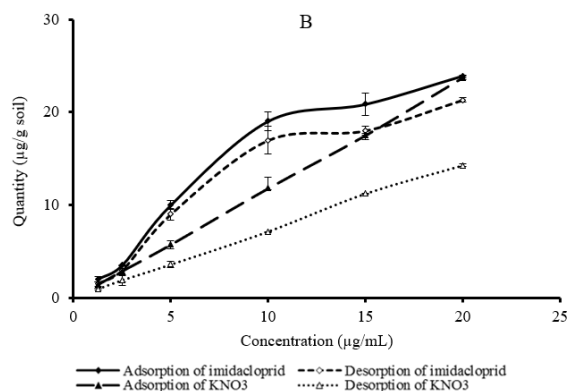


Figure 2. Non-competitive sorption isotherm (A) and competitive sorption isotherm (B) of imidacloprid and KNO₃ in alluvial soil.

3. Results

3.1. Non-competitive sorption of the tested agrochemicals

The non-competitive adsorption/desorption of imidacloprid and KNO₃ into alluvial soil and sandy soil were studied at initial concentrations ranging from 1.25 to 20 µg/mL (Figure 2A and Figure 3A). Non-competitive adsorption was greater than Non-competitive desorption in both alluvial and sandy soils, especially at high concentrations. Similarly, the adsorption and desorption of the pesticide imidacloprid were greater than those of

KNO₃ in the two soils tested, except at a concentration of 20 µg/mL in sandy soil. The percentages of non-competitive adsorption were 44 and 36% in the alluvial soil and 47 and 35% in the sandy soil, while the percentages of non-competitive desorption were 26 and 19% in the alluvial soil and 27 and 21% in the sandy soil for the imidacloprid pesticide and KNO₃ fertilizer, respectively. It is clear from this that imidacloprid adsorption was greater on sandy soil than on alluvial soil, while the opposite was true for KNO₃.

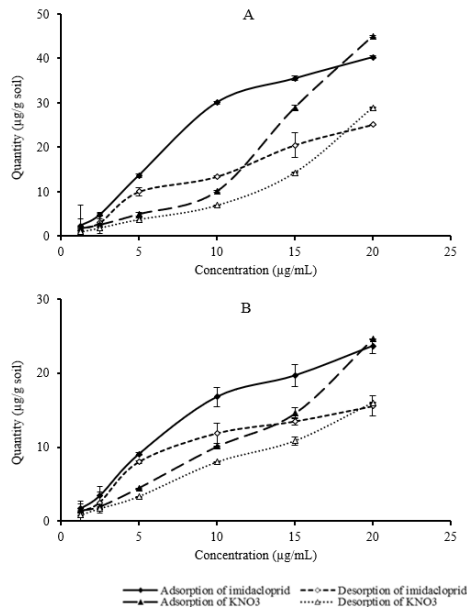


Figure 3. Non-competitive sorption isotherm (A) and competitive sorption isotherm (B) of imidacloprid and KNO₃ in sandy soil.

4.2. Competitive sorption of the tested agrochemicals

The results for competitive adsorption and competitive desorption of the imidacloprid pesticide and KNO₃ fertilizer are presented in Figure 2B and Figure 3B. It was found that the forms of competitive adsorption and competitive desorption of the tested agrochemicals take the same forms as non-competitive sorption, with the differences in the amount of adsorption and desorption.

Table 2. Parameters of the Langmuir model and some parameter isotherms

| Parameters | Alluvial soil | | | | Sandy soil | | | |
|----------------------------|-----------------|------------------|--------------|------------------|-----------------|------------------|--------------|------------------|
| | Non-competitive | | Competitive | | Non-competitive | | Competitive | |
| | Imidacloprid | KNO ₃ | Imidacloprid | KNO ₃ | Imidacloprid | KNO ₃ | Imidacloprid | KNO ₃ |
| Adsorption isotherm | | | | | | | | |
| Average (%) | 44.102 | 36.022 | 29.520 | 23.488 | 47.062 | 34.732 | 27.623 | 21.278 |
| Kd | 0.789 | 0.563 | 0.419 | 0.307 | 0.889 | 0.532 | 0.382 | 0.270 |
| q _m | -204.082 | 588.235 | -1428.571 | -1666.667 | -27.473 | 34.364 | -204.082 | 588.235 |
| b | -0.005 | 0.003 | -0.002 | -0.002 | -0.067 | 0.074 | -0.005 | 0.003 |
| R ² | 0.974 | 1.000 | 0.973 | 1.000 | 0.966 | 0.917 | 0.974 | 1.000 |
| SE | 1.493 | 0.570 | 0.509 | 0.384 | 0.577 | 0.480 | 1.031 | 0.134 |
| Desorption isotherm | | | | | | | | |
| Average (%) | 26.092 | 19.395 | 25.966 | 14.568 | 27.446 | 21.152 | 19.614 | 15.186 |
| Kd | 1.449 | 1.166 | 7.307 | 1.633 | 1.399 | 1.558 | 2.449 | 2.493 |
| q _m | 16.750 | 40.650 | -10.352 | 50.251 | 16.556 | -454.545 | 16.750 | 40.650 |
| b | 0.006 | 0.010 | -0.030 | 0.010 | 0.015 | -0.001 | 0.006 | 0.010 |
| R ² | 0.990 | 0.992 | 0.838 | 0.999 | 0.907 | 0.706 | 0.990 | 0.992 |
| SE | 1.197 | 0.539 | 0.609 | 0.184 | 1.935 | 0.185 | 0.978 | 0.115 |

The presence of both imidacloprid pesticide and KNO₃ fertilizer had a clear effect on the adsorption and desorption processes. The presence of KNO₃ led to a reduction in the amount of imidacloprid from 44.1 and 47.1% to 29.5 and 27.6% for adsorption and from 26.1 and 27.5% to 26.0 and 19.6% for desorption in alluvial and sandy soils, respectively. The presence of imidacloprid also led to a decrease in KNO₃ from 36.0 and 34.7% to 23.5 and 21.3% for adsorption and from 19.4 and 21.2% to 14.6 and 15.2% for desorption in alluvial soil and sandy soil, respectively.

4.3. Langmuir model

Regression analysis was used to fit the linearized expression of the Langmuir isotherm model to the adsorption and desorption data for imidacloprid and KNO₃ in alluvial soil and sandy soil. The values of the Langmuir constant and some parameter isotherms are presented in Table 2. The values of parameters derived from the tested agrochemicals in alluvial and sandy soils were found to be different. Langmuir expression produced higher of correlation coefficients for all the adsorption and desorption of the tested agrochemicals into soils except for the non-competitive desorption of KNO₃ in sandy soil (R² = 0.706). The Langmuir model agreed with the experimental data for imidacloprid and KNO₃ for non-competitive sorption and competitive sorption into the tested soils, as indicated by the higher values of the determination coefficient and lower values of the standard error. These Kd values and soil property values are contained in many agrochemical databases and are used to predict agrochemical behaviour. Kd is defined as the ratio of the agrochemical concentration in the soil to that in the equilibrium solution at a certain equilibrium concentration, and was computed as the average of Kd values corresponding to different concentrations. The Kd values were 0.270 to 0.889 for adsorption and 1.166 to 7.307 for desorption into the tested soils.

3.2. Effect of the interaction between imidacloprid and KNO₃ on wheat germination

The data in Table 3 show a reduction in the relative root, and shoot elongation percentage when the pesticide imidacloprid was combined with KNO₃ at different concentrations (1.25 to 20 µg/mL), and the root length decreased to 6.54, 6.39, 5.46, 4.55, 4.45, and 3.79 cm, respectively compared with that of the control (6.62 cm) under the experimental conditions of the wheat seeds in alluvial soil. Additionally, the shoot length significantly decreased to 4.24, 4.92, 4.67, 4.39, 4.31, and 3.75 cm, compared with that of the control (4.99 cm). When we used imidacloprid individual at the same concentrations, the experiment revealed a significant decreases in root length of 6.58, 6.08, 4.38, 4.26, 3.27, and 2.45 cm compared with that of the control (6.25 cm); and a significant decreases in shoot length of 4.84, 4.66, 3.53, 3.46, 3.29, and 3.02 cm compared with that of the control (4.99 cm). In contrast, the use of KNO₃ fertilizer resulted in a significant increase in root, and shoot length at concentrations of (1.25, 2.5, 5, 10, and 15 µg/mL) when compared to those of the control, but the concentration of 20 µg/mL resulted in a decrease in root and shoot length when compared to those of the control. Furthermore, the data revealed a modest decrease in the germination index when KNO₃ was combined with imidacloprid compared to that of the control, but the decrease was greater when imidacloprid was used alone. When using KNO₃ alone, the germination index increased, reaching 104.3, 124.2, 107.81, and 107.68% compared to that of the control (100%) at concentrations of 1.25, 2.5, 5, and 10 ppm, respectively, but concentrations of 15 and

20 µg/mL caused a decrease in the germination index of 69.96 and 44.76%, respectively, when compared to that of the control (100%).

Table 4 shows a reduction in the relative root and shoot elongation percentages when imidacloprid and KNO₃ were combined in sandy soil. The root lengths decreased to 4.32, 3.82, 3.21, 2.57, 2.07, and 1.30 cm, respectively compared with those of the control (5.02 cm). Additionally, the shoot length significantly decreased to 4.43, 3.75, 3.53, 3.15, 3.03, and 1.40 cm, respectively compared with that of the control (4.72 cm) of the wheat seeds. However, when we used imidacloprid only at the same concentrations, a significant decrease in root length of 3.63, 2.88, 2.57, 2.42, 2.03, and 1.12 cm was detected compared with that of the control (5.02 cm), while shoot length significantly decreased to 3.75, 3.06, 2.70, 2.41, 2.20, and 1.66 cm, respectively compared with that of the control (4.72 cm). On the other hand, the use of KNO₃ at concentrations of (1.25, 2.5, 5, and 10 µg/mL) led to significant increases in root and shoot length compared with those of the control, but at concentrations of 15 and 20 µg/mL, it induced a reduction in root and shoot length compared with those of the control. Additionally, the data showed that there was a slight decrease in the germination index when using KNO₃ with imidacloprid compared with the control, but the decrease was greater when using imidacloprid alone. When KNO₃ was used alone, the germination index increased to 118% compared with that of the control (80%) at a concentration of 5 µg/mL, but at 15 and 20 µg/mL, KNO₃ decreased the germination index to 69.96% and 44.76%, respectively compared with that of the control (80%).

Table 3. The non-competitive and competitive effects of imidacloprid and KNO₃ on wheat seed germination in alluvial soil

| Treatments | Root (cm) | Relative root elongation (%) | Shoots (cm) | Relative shoot elongation (%) | Relative Germination (%) | Germination index |
|---|-----------------------------|------------------------------|---------------------------|-------------------------------|--------------------------|-------------------|
| Control | 6.62 ± 0.18 ^{cd} | 100 | 4.99±0.08 ^{cde} | 100 | 100 | 100 |
| Concentrations(µg/mL) Imidacloprid | | | | | | |
| 1.25 | 6.58 ± 0.14 ^{bc} | 99.40 | 4.84±0.12 ^{abcd} | 96.99 | 90 | 89.46 |
| 2.5 | 6.08 ± 0.31 ^{cd} | 91.84 | 4.66±0.53 ^{bcde} | 93.39 | 80 | 73.47 |
| 5 | 4.38 ± 0.31 ^{efgh} | 66.16 | 3.53±0.28 ^e | 70.74 | 70 | 46.31 |
| 10 | 4.26 ± 0.34 ^{efgh} | 64.35 | 3.46±0.31 ^{de} | 69.34 | 60 | 38.61 |
| 15 | 3.27± 0.13 ^{hi} | 49.40 | 3.29±0.22 ^{de} | 65.93 | 50 | 24.70 |
| 20 | 2.45 ± 0.16 ⁱ | 37.01 | 3.02±0.33 ^e | 60.52 | 50 | 18.51 |
| Concentrations(µg/mL) KNO ₃ | | | | | | |
| 1.25 | 6.91± 0.18 ^{bc} | 104.38 | 4.94±0.18 ^{bcde} | 99.00 | 100 | 104.38 |
| 2.5 | 8.25 ± 0.05 ^a | 124.62 | 6.01±0.12 ^{abc} | 120.44 | 100 | 124.62 |
| 5 | 7.93 ± 0.18 ^{ab} | 119.79 | 6.40±0.17 ^{ab} | 128.26 | 90 | 107.81 |
| 10 | 7.92 ± 0.11 ^{ab} | 119.64 | 6.63±0.04 ^a | 132.87 | 90 | 107.68 |
| 15 | 7.11 ± 0.04 ^{abc} | 107.40 | 4.99±0.05 ^{bcde} | 100.00 | 80 | 85.92 |
| 20 | 5.53 ± 0.39 ^{de} | 83.53 | 3.74±0.30 ^{de} | 74.95 | 70 | 58.47 |
| Concentrations(µg/mL) Imidacloprid + KNO ₃ | | | | | | |
| 1.25 | 6.54 ± 0.15 ^{cd} | 98.79 | 4.24± 0.30 ^{de} | 84.97 | 80 | 79.03 |
| 2.5 | 6.39 ± 0.16 ^{cd} | 96.55 | 4.92±0.12 ^{bcde} | 98.60 | 80 | 77.24 |
| 5 | 5.46 ± 0.08 ^{def} | 82.48 | 4.67±0.13 ^{cde} | 93.59 | 80 | 65.98 |
| 10 | 4.55 ± 0.02 ^{efgh} | 68.73 | 4.39±0.04 ^{cde} | 87.98 | 70 | 48.11 |
| 15 | 4.45 ± 0.39 ^{efg} | 67.22 | 4.31±0.56 ^{de} | 86.37 | 70 | 47.05 |
| 20 | 3.79 ± 0.34 ^{gh} | 57.25 | 3.75±0.48 ^{de} | 75.15 | 70 | 40.08 |
| LSD | 1.16 | | 1.40 | | | |

4. Discussion

The results obtained show that the presence of imidacloprid pesticide and KNO₃ fertilizer together affects the behavior of their adsorption and desorption into the tested soils. This finding is consistent with prior research findings (Schalscha *et al.* 1974; Kamewada 1996; Moreira and Alleoni 2010; Pateiro-Moure *et al.* 2010; Jin *et al.* 2013; Wang *et al.* 2020; Esfandiar *et al.* 2022; Abd-Eldaim *et al.* 2023). The presence of both atrazine and imidacloprid decreased the adsorption of carbendazim onto silty sand soil (Jin *et al.* 2013). Pateiro-Moure *et al.* (2010) performed competitive and/or non-competitive sorption experiments on diquat, paraquat, and difenzoquat in eight types of soil and found paraquat to

be the most powerful in terms of adsorption, followed by diquat, and difenzoquat in non-competitive experiments. However, there was a considerable effect between the divalent cationic herbicides paraquat and diquat, as well as between them and the monovalent herbicide difenzoquat, difenzoquat had little effect on paraquat and diquat in competitive experiments. The interaction between KNO₃ and K₂SO₄ adsorption on soil was evaluated by Kamewada (1996), who reported a decrease in the amount of KNO₃ adsorbed with increasing concentrations of K₂SO₄ or KNO₃. The competitive and non-competitive adsorption data were described by the Langmuir equation in previous studies by Moreira and Alleoni (2010).

Table 4. The non-competitive and competitive effects of imidacloprid and KNO₃ on wheat seed germination in sandy soil

| Treatments | Root (cm) | Relative root elongation (%) | Shoots (cm) | Relative shoot elongation (%) | Relative Germination (%) | Germination index |
|-----------------------|---------------------------------|------------------------------|---------------------------|-------------------------------|--------------------------|-------------------|
| Control | 5.02±0.04 ^{abc} | 100 | 4.72±0.14 ^{cd} | 100 | 80 | 80 |
| Concentrations(µg/mL) | Imidacloprid | | | | | |
| 1.25 | 3.63±0.19 ^{de} | 72.31 | 3.75±0.18 ^{ef} | 79.45 | 70 | 50.62 |
| 2.5 | 2.88±0.20 ^{efg} | 57.37 | 3.06±0.02 ^{fg} | 64.83 | 70 | 40.16 |
| 5 | 2.57±0.20 ^{fg} | 51.19 | 2.70±0.12 ^{ghi} | 57.20 | 70 | 35.70 |
| 10 | 2.42±0.15 ^{fg} | 48.21 | 2.41±0.12 ^{hij} | 51.06 | 60 | 28.93 |
| 15 | 2.03±0.02 ^{gh} | 40.44 | 2.20±0.02 ^{ijk} | 46.61 | 50 | 20.22 |
| 20 | 1.12±0.04 ^h | 22.31 | 1.66±0.11 ^k | 35.17 | 50 | 11.16 |
| Concentrations(µg/mL) | KNO ₃ | | | | | |
| 1.25 | 5.31±0.01 ^{ab} | 105.78 | 5.40±0.30 ^{bc} | 114.41 | 90 | 94.5 |
| 2.5 | 5.60±0.04 ^a | 111.55 | 6.16±0.13 ^{ab} | 130.51 | 90 | 100.3 |
| 5 | 5.93±0.03 ^a | 118.13 | 6.43±0.22 ^a | 136.23 | 100 | 118.13 |
| 10 | 5.12±0.30 ^{abc} | 101.99 | 4.88±0.19 ^{cd} | 103.39 | 90 | 91.79 |
| 15 | 4.39±0.32 ^{bcd} | 87.45 | 4.43±0.29 ^{de} | 93.86 | 80 | 69.96 |
| 20 | 3.21±0.21 ^{ef} | 63.94 | 3.31±0.18 ^{fg} | 70.13 | 70 | 44.76 |
| Concentrations(µg/mL) | Imidacloprid + KNO ₃ | | | | | |
| 1.25 | 4.32±0.34 ^{cd} | 86.06 | 4.43±0.14 ^{de} | 93.96 | 80 | 68.85 |
| 2.5 | 3.83±0.18 ^{de} | 76.29 | 3.75±0.20 ^{ef} | 79.45 | 70 | 53.40 |
| 5 | 3.21±0.05 ^{ef} | 63.94 | 3.53±0.13 ^{efg} | 74.79 | 70 | 44.76 |
| 10 | 2.57±0.25 ^{fg} | 51.20 | 3.15±0.15 ^{fghi} | 66.74 | 60 | 30.72 |
| 15 | 2.07±0.07 ^{gh} | 41.24 | 3.03±0.22 ^{fghi} | 64.19 | 60 | 24.74 |
| 20 | 1.30±0.05 ^h | 25.90 | 1.40±0.08 ^k | 29.66 | 60 | 15.54 |
| LSD | 0.90 | | 0.89 | | | |

Through our study on the effect of imidacloprid on the germination of wheat seeds in alluvial and sandy soils, it became clear that imidacloprid had a negative effect on both root and shoot length and on the germination index. These results were consistent with what has been studied in many studies. Murthy and Rajesh (2004) reported that the germination percentage, growth, plant weight, vigour index, and other parameters decreased when imidacloprid was applied to rice seeds that had not been dried before germination (Pulikkal *et al.* 2015). Additionally, it was discovered that in these measures, damage increased with longer periods of exposure and greater imidacloprid concentrations. Pulikkal *et al.* (2015) investigated the effect of the insecticide imidacloprid on cucumber plants and discovered that the pesticide inhibited seed

germination and vigor. Deformities such as swelling, chlorosis, cotyledon root formation, root tip burning, a decrease in root length, and hypocotyl deficiency were also detected with increasing imidacloprid concentrations. Shaker *et al.* (2016) evaluated the effect of the overuse of four common insecticides (lambda-cyhalothrin, imidacloprid, alpha-cypermethrin, and emamectin benzoate) on tomato plant germination, photosynthetic pigments, and seedling vigour. The results showed that using an amount exceeding the permissible dose of these pesticides led to a decrease in seed germination; while inhibiting tomato growth. Zhang *et al.* (2022) reported that, depending on growth factors and membrane lipid peroxidation results under various nitrogen supply conditions, imidacloprid limits maize growth. According to

the results of our study, which are consistent with previous research, potassium nitrate helped reduce the negative impact of abiotic stress resulting from the use of the pesticide imidacloprid on wheat seeds and led to improvements in the root length, shoot length, and germination index of wheat seeds. Steiner *et al.* (2018) reported that KNO₃ improved wheat seedling germination, early growth, and the vigour index. KNO₃ can enhance seed germination by producing nitric oxide when plants are exposed to salt stress (Sanz *et al.* 2015; Parankusam *et al.* 2017). Additionally, using KNO₃ as a foliar treatment improves water availability, nutrient uptake, chlorophyll content, and photosynthesis (Marschner *et al.* 1995; Egilla *et al.* 2001). Tanin *et al.* (2023) demonstrated that KNO₃ is important for postponing leaf senescence and enhancing resistance to abiotic and biotic stressors.

5. Conclusion

In general, the adsorption of the tested agrichemicals was greater than their desorption into both soils. The adsorption of the pesticide imidacloprid was greater than that of KNO₃ in both soils, and it was greater in sandy soils than in alluvial soils; and was greater in non-competitive adsorption than in competitive adsorption. While KNO₃ adsorption was lower than imidacloprid adsorption in the tested soils, greater in the alluvial soil than in the sandy soil, and greater in the non-competitive adsorption than in the competitive adsorption. The Langmuir equation was used and was compatible with the experimental results. The pesticide imidacloprid led to a reduction in wheat seed germination, which was more evident in sandy soil. This may be due to the lack of nutrients compared to those in alluvial soil, while when using imidacloprid with KNO₃, KNO₃ helped reduce the severity of the negative effect resulting from the pesticide. The use of KNO₃ alone also improved root and shoot length and the germination index, but at high concentrations, KNO₃ inhibited plant growth.

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