Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

ARTICLE

Effect of Moisture Content on Selenate and Selenite Determination Using DGT

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ABSTRACT

Traditional studies on transforming selenate and selenite are often limited by static measurements and low spatial resolution. They do not fully consider the impact of moisture content. This paper uses the DGT (diffusive gradients in thin films) technique to deeply explore how moisture changes affect the transformation of selenate and selenite in the environment (changes in properties over time). First, representative soil samples (loess) are prepared, and their moisture content is adjusted. Fixed concentrations of selenate and selenite are added, and then the DGT device simulates their migration in the natural environment. The experiment covers drought, moisture, and high moisture environments, and the experiment is repeated under each condition to ensure the accuracy of the data. The sample quality is verified and further analyzed by ion chromatography (IC) and atomic absorption spectroscopy (AAS). This article uses DGT technology to study the influence of moisture content on the migration and transformation of selenate and selenite in soil. Results indicate that increased moisture content leads to higher concentrations, diffusion rates, and DGT capture efficiency of both

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ARTICLE INFO
Received: 23 January 2025 | Revised: 4 March 2025 | Accepted: 5 March 2025 | Published Online: 9 May 2025
DOI: https://doi.org/10.30564/jees.v7i5.8534

CITATION
Zhang, Y., Wang, X., Liu, Y., et al., 2025. Effect of Moisture Content on Selenate and Selenite Determination Using DGT. Journal of Environmental & Earth Sciences. 7(5): 401–412. DOI: https://doi.org/10.30564/jees.v7i5.8534

selenium species, highlighting the importance of moisture in their environmental behavior. When the moisture content increased from 25% to 65%, the coefficient of variation of selenate and selenite increased. The DGT technique proved effective in capturing spatial heterogeneity and providing high-precision measurements, offering robust data to advance research on selenium behavior in soils.

Keywords: Diffusive Gradients in Thin Films; Selenate and Selenite; Transformation Effect Study; Moisture Content; Device Deployment

1. Introduction

Monitoring and research on selenium, especially selenate and selenite, have become critical as environmental pollution is a growing problem. Selenium is a trace element that is vital in many organisms and ecosystems. It is widely present in soil and aquatic environments. As an environmental pollutant, the presence of selenium poses a risk to ecosystem health and human health. Among the various chemical forms of selenium, selenate and selenite have been identified as the ones to be focused on. Their environmental dynamics, including behavior and transformation processes, are affected by many factors, especially moisture content and oxidation-reduction conditions, which can significantly change their migration and bioavailability. Traditional selenium research methods mainly focus on static analysis, usually treating moisture content as a fixed variable and ignoring the impact of moisture changes on the behavior of selenate and selenite. In particular, the lack of dynamic monitoring and spatial resolution has led to important knowledge gaps in the comprehensive understanding of selenium behavior. Therefore, there is an urgent need for innovative research methods, especially in studying how different moisture contents affect the transformation, migration, and bioavailability of selenate and selenite in soil environments.

The DGT (diffusive gradients in thin films) technique has become an effective tool for dynamic measurement of solute concentration and diffusion behavior. Compared with traditional static techniques, DGT can provide higher spatial resolution and more detailed temporal data, making it very suitable for studying the migration and transformation processes of selenite and selenite under different moisture environments. The greatest advantage of the DGT technique is the ability to simultaneously assess changes in selenide concentrations under different moisture conditions, providing a new perspective on understanding the dynamic behavior of these chemical species in the environment and ultimately supporting environmental management and remediation strategies. The influence mechanism of moisture conditions on selenium behavior can be used to optimize selenium pollution remediation plans.

This paper aims to quantify the effect of different moisture levels on selenate and selenite concentrations. It also aims to determine the influence of moisture content on the diffusion rates of selenate and selenite, and to evaluate the performance of the DGT technique under varying moisture conditions. The experiments are conducted to dynamically monitor the concentration changes of selenate and selenite and their chemical transformation processes by setting different moisture conditions to reveal the specific effects of moisture changes on the transformation process of the two selenium compounds. The main contribution of this paper is the application of DGT technology to fill the gaps in traditional research in spatial resolution and time scale, providing a new theoretical basis for the role of moisture content in selenium pollution control.

2. Related Work

Selenium is an important trace element that has many positive effects on human health and diseases[1]. There is an exploration that pointed out that changes in moisture, especially in the high-frequency range, can significantly change the structure's frequency response. The increase in moisture content increases the structure's mass and reduces its inherent vibration frequency, thereby causing changes in the frequency spectrum characteristics[2]. At the same time, with the increasingly prominent trend of refined agricultural management, the precision and stability of soil moisture sensors have also received increasing attention[3]. In addition, although selenium is essential for plant growth, excessive selenium may be toxic to crops[4, 5]. Selenates and selenites, as selenium-containing compounds widely present in the environment, are often found in soil and water[6, 7]. In-depth research on the transformation mechanism of these compounds and their impact on the environment can help assess the potential risks that selenium compounds may pose to ecosystems[8, 9]. Therefore, it is urgent to research how moisture content affects the transformation process of selenate and selenite.

Existing studies are not fully aware of how water content affects the transformation process of selenates and selenites and the dynamic changes of their environmental behavior. However, DGT technology, with its high sensitivity and dynamic monitoring capability, provides an innovative means to study this knowledge gap, which has important novelty and application prospects. The DGT technique[10, 11] has gained widespread attention for its unique advantages in quantifying elements and compounds in soil and aquatic environments due to its high sensitivity, high spatial resolution, and strong dynamic monitoring capabilities[12, 13]. Wei et al.'s[14] research showed that DGT exhibited excellent sensitivity and spatial resolution in assessing heavy metals, nutrients, and organic pollutants. Bai et al's[15] analysis showed that DGT could represent the heavy metals absorbed by plants more precisely, especially in the assessment of heavy metal pollution. Pantoja and Garelick[16] reviewed the potential of DGT in environmental radionuclide monitoring and pointed out that it has broad application prospects. Kodithuwakku et al.[17] considered that DGT could effectively capture the dynamic changes of nitrate and ammonium in soil, providing a new tool for soil nutrient management. Guan et al.[18] reviewed the application of DGT in soil nutrient and pollutant analysis, bioavailability assessment, modeling, and mapping. The DGT technique has broad application prospects in soil environmental monitoring, which helps to deepen the understanding of the migration and transformation behavior of soil pollutants. In summary, the effect of moisture content on the transformation of selenate and selenite could be studied using the DGT technique.

3. Monitoring Moisture Content and Compound Behavior

3.1. Sample Preparation

Soil samples were chosen from representative experimental sites. The sampling depths were 0–20 cm (active root growth zone). Soil from 3 different positions was mixed at each sampling point. The collected samples were put into a clean plastic bag immediately to avoid exposure to air for too long. The soil texture is silty with relatively little sand and moderate clay content. The organic content is between 0.5% and 2%, the pH value is generally between 7.5 and 8.5, and it is slightly alkaline.

The study selects high-precision sensors to monitor soil moisture status in real-time. All soil samples collected were sieved to remove particles larger than 2 mm and air-dried to constant weight. During the air-drying process, high temperatures or direct sunlight should be avoided.

The air-dried soil samples were re-moistened according to the experimental requirements. Different volumes of deionized water were added to control the moisture content. The soil was stirred evenly before weighing to ensure moisture was evenly distributed. Deionized water was produced by a laboratory deionizer with an electrical conductivity of less than 0.1 µS cm^{-1}.

The dry weight of the soil was calculated using the oven drying method (105 °C, 24 hours), and the moisture content was calculated based on the ratio of wet soil weight to dry soil weight. **Figure 1** shows details.

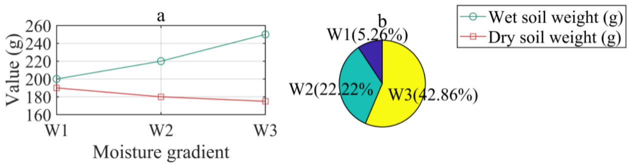


Figure 1. Moisture content calculation: (**a**) wet soil weight and dry soil weight data; (**b**) moisture content data.

Figure 1 shows the wet soil and dry soil weights with changes in moisture content. The horizontal axis of **Figure 1a** represents the moisture gradient (low moisture W1, moderate moisture W2, and high moisture W3). The wet soil weight increases with the increase of the moisture gradient. The dry soil weight shows a downward trend, indicating that the increase in moisture leads to an increase in the proportion of moisture in the soil and a decrease in the dry soil portion. In **Figure 1b**, the moisture content is 5.26%, 22.22%, and 42.86%, respectively, showing that the moisture content of the soil increases significantly with the increase of the moisture gradient. This indicates that the soil can better retain moisture under higher moisture conditions and is more conducive to plant growth. Overall, these data reveal the relationship between moisture and soil weight and moisture content, providing an essential reference for soil moisture management.

Under low moisture conditions, the soil moisture content is low, which affects the dissolution and migration of nutrients in the soil. With the increase of water content, a moderate water state helps to improve the water absorption capacity of plant roots and promote the effective utilization of nutrients. Under high moisture conditions, excessive moisture may cause the soil permeability to decrease, affecting the respiration of the root system.

Water samples were collected in glass containers (must be uncontaminated deionized water) and then sealed and stored in a refrigerator until the start of the experiment (storage at 4 °C). High-purity sodium selenate and sodium selenite standard solutions were diluted to ensure the consistency of the initial concentrations of selenate and selenite at different moisture contents. The solution was prepared precisely using an analytical balance with Formula (1) [19]:

$$C = \frac{m}{V} \tag{1}$$

C refers to the solute concentration in the sample (mg L^{-1}); m refers to the mass of the solution (mg); V refers to the volume of the solution (L).

The selenate and selenite solutions were added to the soil evenly in batches and mixed thoroughly. For water samples, the addition steps of selenate and selenite were similar to those of soil samples. A precise dosing pump was used to add selenate and selenite solutions to water samples.

Treated soil samples were sealed and stored at room temperature after humidification to maintain the original moisture status of the samples. Treated water samples were then kept at a constant temperature. All samples were left to stand for at least 24 hours to ensure stability.

The quality of the samples was verified before and after the experiment, and the concentrations of selenate and selenite were determined using ion chromatography (IC) [20, 21] and atomic absorption spectroscopy (AAS) [22, 23] techniques. To ensure the accuracy and reliability of IC and AAS analysis, high-purity standard substances and multi-point calibration were used to generate standard curves, ensuring the quantitative capability of the instrument. Secondly, potential interference was detected using blank samples, and the reproducibility and precision of the data were evaluated through repeated measurements of technology and samples.

3.2. Experimental Design

The moisture content gradient is used to simulate three typical environments: drought, moisture, and high moisture. **Table 1** presents the experimental design and conditions.

Each experimental group must be tested three times or more independently to ensure the results. The equipment and containers used in the experiment must be strictly cleaned and disinfected to avoid cross-contamination. The rationale for choosing specific water content levels W1, W2, and W3 to represent drought, moisture, and high moisture is largely based on studies of plant growth and soil water status.

In arid environments, plant roots tend to concentrate in shallow active areas, so a W1 placement depth of 10 cm is a reasonable location, which can effectively simulate the absorption area of plant roots. In moist environments, soil water is more evenly distributed, and nutrient availability and migration ability are higher. Choosing a depth of 20 cm can better reflect the nutrient utilization of plant roots in an environment with moderate water content. In excessively wet environments, the upper layer of the soil may be flooded or hypoxic, resulting in excessive nutrient solubility or leaching to deeper layers. DGT is placed at a depth of 30 cm to monitor changes in nutrient availability as excess water percolates downward.

The DGT device is buried in soil samples at different depths to simulate the migration of selenate and selenite in different soil layers. In water samples, the DGT device is suspended in the center of the water body to ensure that the water samples around the device can fully contact and capture selenide through a diffusion mechanism.

The placement of the DGT device and the experimental time in each sample are precisely recorded. The experimental duration is set to 7 days. Samples are collected at different time points after the DGT device is deployed. The concentration changes of selenate and selenite are analyzed by IC and AAS. The concentration data and the changes in moisture content of each experimental group are compared to explore the migration, transformation, and transformation process of compounds under different moisture conditions.

Fick's first law can be used to quantify the diffusion flux of selenium from soil micropores to plant root surfaces, thereby assessing the bioavailability of selenium. Fick's first diffusion law is used for the selenate and selenite concentration gradient data recorded by DGT to calculate the diffusion

Table 1. Temperature, time, and equipment placement depth corresponding to different moisture contents.

Moisture Gradient	Moisture Content	Simulated Environment	Temperature (20 ± 2 °C)	DGT Placement Depth	Experimental Duration	Repetitions
W1	10%	Drought	Yes	10 cm	7 days	≥3
W2	20%	Moisture		20 cm		
W3	30%	High moisture		30 cm		

rate of the solute[24, 25]:

$$J = -D\frac{\partial C}{\partial x} \tag{2}$$

D refers to the diffusion coefficient, and $\frac{\partial C}{\partial x}$ refers to the concentration gradient.

Combined with the technical characteristics of DGT, it can be converted into through the formula[26]:

$$D = \frac{\Delta m \cdot \Delta g}{t \cdot A \cdot C} \tag{3}$$

Δm is the change in solute mass; ΔG is the gel thickness; t refers to the experimental time; A refers to the effective cross-sectional area of the device.

The calculated data should be correlated with the change in moisture content. Data fitting and regression analysis are performed using SPSS (Statistical Package for the Social Sciences) statistical software[27, 28], as shown in **Figure 2**.

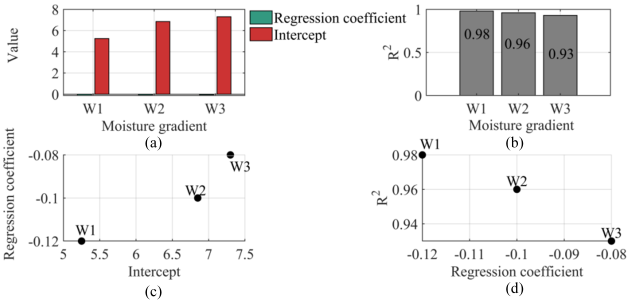


Figure 2. Data fitting and regression results: (**a**) regression coefficient and intercept; (**b**) coefficient of determination data; (**c**) relationship between regression coefficient and intercept; (**d**) relationship between regression coefficient and coefficient of determination.

Figure 2 shows the data fitting and regression results. The p value of the regression coefficient was less than 0.05. **Figure 2a** mainly displays the data of regression coefficients and intercepts, while **Figure 2c** shows the corresponding relationship between them. It can be observed that the regression coefficient of W1 is –0.12, indicating that plant growth or soil nutrient availability is inhibited under water deficient conditions. The intercept is 5.25, indicating that in the extreme case of zero moisture content, the baseline value of this indicator is 5.25. The regression coefficient of W2 is –0.10. Compared with W1, this indicator has sligtly lower sensitivity to changes in water content, as plant growth or soil nutrient availability is relatively stable under moderate water conditions. The intercept is 6.85, and the baseline value has increased, indicating that the overall level of this indicator is relatively high under moderate humidity conditions. The regression coefficient of W3 is –0.08, indicating that under high moisture conditions, the sensitivity of the index to moisture changes further decreases. This is because under high humidity conditions, plant growth or soil nutrient availability approaches saturation. The intercept is 7.30, with the highest baseline value, indicating that the overall level of this indicator is highest under high humidity conditions.

Figure 2b shows the R^2 value, and **Figure 2d** shows the relationship between regression coefficients and R^2 value. Among them, the R^2 value of W1 is as high as 0.98, indicating that the regression model has a high fit to low water grouping data, and the model can explain 98% of the data changes. The R^2value of W3 is 0.93, which is lower than the other two groups, indicating a slight decrease in the fitting of the model to the high moisture group data, as there are other factors affecting the indicators under high moisture conditions.

3.3. DGT Device Deployment

The DGT device used in this paper is a standard thin-film DGT device (composed of a polymer film, an adsorbent, and a diffusion layer)[29, 30]. Since selenates and selenites are charged anions, the selection of a strong basic ion exchange resin suitable for anion capture, with its high selectivity and low baseline interference, ensures efficient capture of target ions. Polyvinylidene fluoride is selected as the diffusion layer material, which helps the target ions to diffuse at a controlled rate under simulated moisture conditions. The dimensions of the DGT device (2–4 cm in diameter and 0.1–0.3 mm in diffusion layer thickness) are optimized to provide adequate spatial resolution and sensitivity under different moisture conditions, while the design of the porosity (about 20–30%) balances diffusion efficiency with mechanical strength, ensuring measurement accuracy and long-term stability. It is suitable to study the effect of water content on the transformation process of selenium compounds.

In the soil sample, the DGT device should be carefully inserted into the specific position of the soil sample during deployment, with a depth of 5–10 cm in the soil surface, to avoid direct contact with soil particles. The soil around the DGT device should not be significantly compacted to ensure that selenate and selenite can be evenly diffused into the film area of the device.

During installation, the orientation and position of the DGT device should be kept vertical to ensure that its diffusion film uniformly captures the target compound.

After deployment, the soil samples are kept in a constant moist state and placed in a temperature-controlled laboratory environment. The key factors of dissolved oxygen, pH (Pondus Hydrogenii), and temperature of the water sample are kept consistent, and the DGT device is about 10 cm away from the bottom of the water sample. In soil samples, high moisture content can increase the migration of water, thereby promoting the diffusion rate of selenate and selenite. It can also increase the solubility of selenate and selenite, thereby improving the efficiency of the DGT device in capturing target compounds. In soils with low moisture content, the limiting effect of moisture may lead to a slowdown in the diffusion rate. **Table 2** lists the details.

Table 2. Migration and transformation characteristics of selenate and selenite under different moisture conditions.

Moisture Gradient	Moisture Content	Selenate Concentration	Selenite Concentration (mg L^{-1})	Diffusion Rate (mol m^{-2} s^{-1})	Capture Efficiency (%)
W1	10%	5.0	2.0	1.5×10^{-6}	30
W2	20%	15.0	10.0	2.0×10^{-6}	50
W3	30%	25.0	18.0	3.0×10^{-6}	70

In **Table 2**, with the increase in moisture content, the concentration, diffusion rate, and capture efficiency of selenate and selenite all show a significant positive correlation, reflecting the critical effect of moisture on the migration and transformation of these compounds in the soil.

Under low water conditions, the dry state of the soil may lead to limited ion interaction and migration, reducing the diffusion rate and trapping ability, and thus affecting the bioavailability of selenium in the soil. Therefore, in environmental monitoring and soil remediation applications, maintaining the appropriate moisture content of the soil is critical.

Seven days after the DGT device is deployed, it is carefully removed, and the captured selenate and selenite are analyzed. When removing the device, it is necessary to ensure that the surface of the device is not damaged and to clean it quickly to avoid residual sample material affecting subsequent analysis. The recovered DGT device is immediately chemically analyzed within the scheduled analysis time. If immediate analysis is not possible, the device should be stored in a low temperature refrigerated environment (usually 4 °C) to slow the change or degradation of the compound.

4. Experimental Verification and Analysis

4.1. Data Collection and Analysis

The water sample's moisture content is measured using a conductivity meter to measure the concentration of dissolved substances and then calculated using relevant formulas. After the DGT device is deployed, real-time data collection is performed through its built-in monitoring system. The concentration changes of selenate and selenite are recorded every 1 hour. After the experiment, the DGT device is taken out to separate the gel membrane and absorbent. Subsequently, the gel membrane is washed with deionized water and extracted according to standard operating procedures. The extracted samples are analyzed using high performance liquid chromatography (HPLC) equipment[31, 32]. Before analysis, the HPLC is calibrated using standard solutions of known concentrations. The extracted samples are injected into the HPLC system at appropriate dilutions to ensure that the sample concentration is within the linear range of the instrument. Each sample is repeated three times (a total of 10 samples). The retention time and corresponding peak area of the detected selenate and selenite are recorded in real time. The concentration of each compound in the sample is calculated by comparing it with the standard curve.

The paper used an anion exchange column combined with a carbonate buffer mobile phase, coupled with a UV detector (210–230 nm), and set the flow rate to 1.0 mL min^{-1}. The concentration range of the calibration standard is between 0.01–0.1 mg L^{-1}, and the linear correlation coefficient of the standard curve is 0.99 or above.

SPSS(Statistical Package for the Social Sciences) was used to obtain descriptive statistics of selenate and selenite concentrations under different moisture contents, as shown in **Table 3**.

Table 3. Descriptive statistics of selenate and selenite concentrations at different moisture contents.

Moisture Content (%)	Selenate Concentration (mg L^{-1})		Selenite Concentration (mg L^{-1})	
	Mean ± Standard Deviation	Coefficient of Variation (%)	Mean ± Standard Deviation	Coefficient of Variation (%)
25	50 ± 5	10	30 ± 3	10
35	45 ± 4	8.9	28 ± 2	7.1
45	40 ± 3	7.5	25 ± 2	8
55	35 ± 4	11.4	22 ± 3	13.6
65	30 ± 5	16.7	18 ± 4	22.2

Table 3 shows the descriptive statistics of selenate and selenite concentrations under different moisture content conditions. As the moisture content increases, the concentrations of selenate and selenite show a downward trend. This indicates that the higher the moisture content, the lower the solubility of selenate and selenite in the soil, which may be because, under high moisture conditions, the soil pores are filled with water, reducing the oxygen content, thereby inhibiting the oxidation and dissolution of selenium.

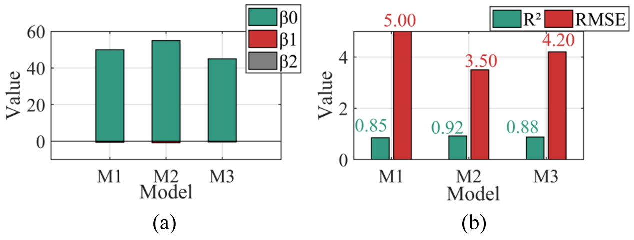
The larger the coefficient of variation (CV), the greater the data volatility[33, 34]. As the moisture content increases, the CV of selenate and selenite concentrations tends to increase. This indicates that the concentrations of selenate and selenite show more significant variability under conditions of increased moisture. This is due to the increased instability within the soil matrix under excessive moisture conditions. In short, moisture content affects the solubility of selenium and its migration and transformation dynamics in the soil environment.

The analysis of variance is applied to compare the effects of different moisture contents on selenate and selenite concentrations and to identify whether there are significant differences between the groups ($p < 0.05$)[35, 36]. A Tukey test is further carried out to determine the specific source of difference if a significant difference is found. The differences between the means of the groups are compared[37, 38].

The Tukey test statistic is calculated, and the corresponding critical value is found. If the difference exceeds the critical value, it is considered that there is a significant difference between the two groups.

Regression analysis is used to explore the relationship between moisture content and the migration rate of selenate and selenite, and mathematical models: linear regression model (M1), polynomial regression model (M2), exponential regression model (M3) are established to quantify the effect of water on the behavior of the compounds. Linear regression models are suitable for initial exploration and simple cases. Polynomial regression models are used to capture nonlinear relationships. Exponential regression models are suitable for exponential growth or decay trends. The R^2 of the model is the largest and the RMSE is the smallest, so it is considered that the model can more accurately reflect the effect of water content on the selenide migration rate.

R^2 and root mean squared error (RMSE) are used to evaluate the model fit. The model with the best fit is selected as the final model, as shown in **Figure 3**.



(a) (b)

Figure 3. Evaluation results of model goodness of fit: (**a**) regression coefficient bar graph; (**b**) coefficient of determination and root mean squared error bar graph.

Figure 3 shows the model's goodness of fit. β0, β1, and β2 refer to different regression coefficients. **Figure 3a** shows the specific data of the regression coefficients, with β0 being relatively highest at W2. **Figure 3b** shows the values of R² and RMSE for different models. Based on these two graphs, the following conclusion can be drawn: different water contents have a significant impact on the concentrations of selenate and selenite.

The polynomial regression model can better describe the relationship between moisture content and migration rate (the R² value of the model was 0.88), indicating that moisture has an inhibitory effect on the migration behavior of compounds.

4.2. Measurement Accuracy

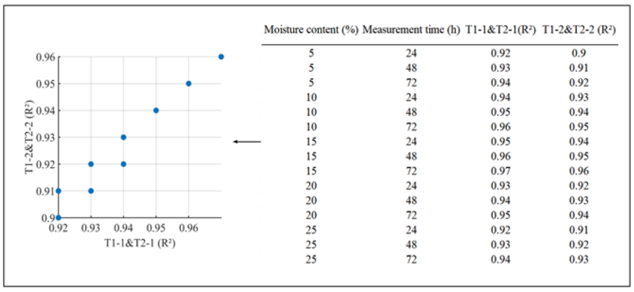
Soil samples are collected from local agricultural areas and divided into five different moisture content groups (5%, 10%, 15%, 20%, 25%). Three replicate samples are prepared for each group. Each sample group is evenly mixed under laboratory conditions to ensure the representativeness and consistency of the samples.

Two samples are randomly selected from each sample group to place the DGT device in this paper, and the other sample is used as a control group. The device is taken out at different time points (24 hours, 48 hours, and 72 hours) for analysis.

After each extraction, IC analysis is performed to determine the concentration of selenate and selenite captured in the DGT device. The concentration of selenate and selenite captured in the DGT device at each time point is recorded (mg L^{-1}). The average concentration and standard deviation are calculated for each moisture content group to ensure the reliability of the statistical results.

The data measured by DGT are compared with the results of standard measurement to evaluate the accuracy of the DGT technique. The correlation between DGT measurement data and standard measurement data is calculated through regression analysis to verify the effectiveness of the DGT technique. **Table 4** and **Figure 4** present the details.

In **Table 4**, T1-1 and T1-2 refer to the DGT measurement of selenate and selenite concentrations, respectively. T2-1 and T2-2 refer to the standard measurement of selenate and selenite concentrations, respectively. D-1 and D-2 refer to the difference between the DGT measurements of selenate and selenite concentrations and the standard measurements, respectively.The data show that with the increase in moisture content, the measured selenate concentrations show an upward trend.



Moisture content (%)	Measurement time (h)	T1-1&T2-1(R²)	T1-2&T2-2 (R²)
5	24	0.92	0.9
5	48	0.93	0.91
5	72	0.94	0.92
10	24	0.94	0.93
10	48	0.95	0.94
10	72	0.96	0.95
15	24	0.95	0.94
15	48	0.96	0.95
15	72	0.97	0.96
20	24	0.93	0.92
20	48	0.94	0.93
20	72	0.95	0.94
25	24	0.92	0.91
25	48	0.93	0.92
25	72	0.94	0.93

Figure 4. Correlation between DGT measurement data and standard measurement data.

The R² values in **Figure 4** are all above 0.9, indicating a good correlation between DGT and the standard selenate and selenite measurement results. In summary, the DGT-based measurement under different moisture content conditions can accurately capture and reflect the concentration changes of selenate and selenite, verifying its reliability and advantages.

4.3. Spatial Resolution

A rectangular water tank (100 cm long, 50 cm wide, and 50 cm high) is used as the simulated environment. A uniform fine sand layer with a thickness of 10 cm is laid at the bottom of the water tank to simulate the soil environment. A gradient concentration area is set in the fine sand layer to simulate spatial heterogeneity by adding different concentrations of selenate and selenite solutions in specific areas.

Ten DGT devices are evenly deployed in the water tank

Table 4. Measurement accuracy of concentration-related data.

Moisture Content (%)	Measurement Time (h)	T1-1 (mg L^{-1})	T1-2 (mg L^{-1})	T2-1 (mg L^{-1})	T2-2 (mg L^{-1})	D-1	D-2
5	24	1.2 ± 0.1	0.5 ± 0.05	1.1	0.45	0.1 ± 0.1	0.05 ± 0.05
5	48	1.3 ± 0.12	0.55 ± 0.06	1.2	0.48	0.1 ± 0.12	0.07 ± 0.06
5	72	1.4 ± 0.15	0.6 ± 0.07	1.3	0.5	0.1 ± 0.15	0.1 ± 0.07
10	24	2.5 ± 0.2	0.9 ± 0.1	2.4	0.85	0.1 ± 0.2	0.05 ± 0.1
10	48	2.6 ± 0.18	0.95 ± 0.09	2.5	0.88	0.1 ± 0.18	0.07 ± 0.09
10	72	2.7 ± 0.25	1.0 ± 0.12	2.6	0.9	0.1 ± 0.25	0.1 ± 0.12
15	24	4.2 ± 0.3	1.8 ± 0.1	4.1	1.7	0.1 ± 0.3	0.1 ± 0.1
15	48	4.3 ± 0.28	1.85 ± 0.15	4.2	1.75	0.1 ± 0.28	0.1 ± 0.15
15	72	4.5 ± 0.35	1.9 ± 0.2	4.3	1.8	0.2 ± 0.35	0.1 ± 0.2
20	24	5.6 ± 0.4	2.3 ± 0.2	5.5	2.2	0.1 ± 0.4	0.1 ± 0.2
20	48	5.8 ± 0.35	2.4 ± 0.15	5.7	2.25	0.1 ± 0.35	0.15 ± 0.15
20	72	6.0 ± 0.5	2.5 ± 0.25	5.9	2.3	0.1 ± 0.5	0.2 ± 0.25
25	24	6.8 ± 0.5	2.8 ± 0.3	6.7	2.6	0.1 ± 0.5	0.2 ± 0.3
25	48	7.0 ± 0.4	2.9 ± 0.35	6.9	2.65	0.1 ± 0.4	0.25 ± 0.35
25	72	7.2 ± 0.6	3.0 ± 0.4	7.1	2.7	0.1 ± 0.6	0.3 ± 0.4

along the length direction (positions increase from 10 cm to 100 cm). One DGT device is deployed at each position, ensuring the device is vertically inserted into the sand layer with the adsorption layer facing downward. The DGT device is deployed in a simulated environment with an exposure time of 48 hours to capture selenate and selenite fully.

The multi-point sampling method of traditional measurement is selected for comparison, and its measurement position is the same as that of the DGT device. Soil samples in the sand layer are collected using a sampling tube, and 3 replicates are collected at each position. The soil samples are mixed evenly. 10 g of sample is taken, and 50 mL of deionized water is added. The samples are extracted by oscillation for 30 minutes. The extract is filtered using a 0.22 μm filter membrane to obtain the sample to be tested. The concentrations of selenate and selenite are analyzed using HPLC.

After 48 hours, the DGT device is removed. The adsorbed gel is washed with deionized water to remove the sample remaining on the surface. The adsorbed gel is placed in a centrifuge tube, and 5 mL of hydrochloric acid solution is added, shaking for 30 minutes to desorb the adsorbed selenate and selenite. The extract is filtered with a 0.22 μm filter membrane to obtain the sample to be tested.

The coefficient of variation and Moran's I index of DGT measurements and multi-point sampling measurements are compared to evaluate the advantage of DGT in capturing spatial heterogeneity. **Table 5** lists the DGT measurements and multi-point sampling measurements, and **Figure 5** presents the coefficient of variation and Moran's I index.

In **Table 5**, T3-1 and T3-2 refer to the measurements of selenate and selenite by the multi-point sampling method. The variation of DGT measurements at different positions is more prominent, indicating a higher spatial resolution.

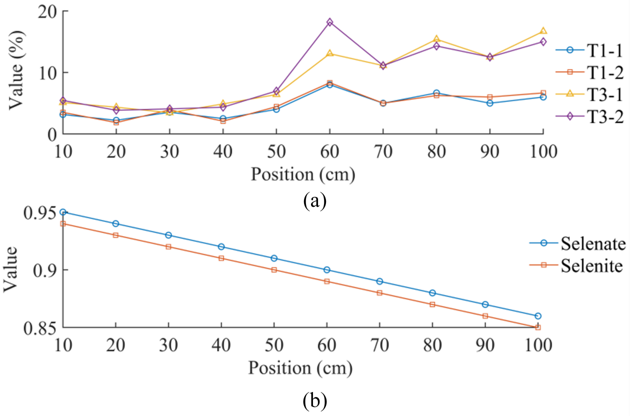


Figure 5. Coefficient of variation of measured values and Moran's I index: (**a**) coefficient of variation of measurement values; (**b**) Moran's I index of selenate and selenite.

In **Figure 5**, the analysis results of the coefficient of variation and Moran's I index further confirm the superiority of DGT in capturing spatial heterogeneity. **Figure 5a** shows the variation of the coefficient of variation between DGT and multi-point sampling measurements at different positions.

Table 5. DGT measurement values and multi-point sampling method measurement values.

Position (cm)	T1-1 (mg L^{-1})	T1-2 (mg L^{-1})	T3-1 (mg L^{-1})	T3-2 (mg L^{-1})
10	95 ± 3	57 ± 2	98 ± 5	55 ± 3
20	90 ± 2	54 ± 1	92 ± 4	52 ± 2
30	85 ± 3	51 ± 2	87 ± 3	49 ± 2
40	80 ± 2	48 ± 1	82 ± 4	46 ± 2
50	75 ± 3	45 ± 2	78 ± 5	43 ± 3
60	25 ± 2	12 ± 1	23 ± 3	11 ± 2
70	20 ± 1	10 ± 0.5	18 ± 2	9 ± 1
80	15 ± 1	8 ± 0.5	13 ± 2	7 ± 1
90	10 ± 0.5	5 ± 0.3	8 ± 1	4 ± 0.5
100	5 ± 0.3	3 ± 0.2	3 ± 0.5	2 ± 0.3

Figure 5b shows the Moran's I index of selenate and selenite at different positions.

The data in **Figure 5a**,**b** shows that the DGT technique can more accurately reflect the spatial distribution of selenate and selenite in the environment, providing more reliable data support for environmental pollution control and water quality protection.

5. Conclusions

In this paper, DGT technology was used to dynamically monitor selenate and selenite. Experiments showed that its sensitivity and accuracy were significantly superior to the traditional multi-point sampling method in high-precision measurement, spatial distribution analysis and low concentration conditions, and it could provide more detailed spatial distribution information of selenium and help optimize environmental monitoring strategies. However, the test scope was limited to specific soil types and water conditions. The universality of DGT technology needs to be verified, and the adaptability of DGT technology under other environmental conditions has not been fully studied. In the future, we can further study the impact of environmental factors on selenium behavior, optimize experimental design, develop automated analysis and data processing methods, improve actual monitoring efficiency, study the dynamic distribution mechanism of selenium under the interaction of multiple environmental factors, and promote the application of DGT in complex environmental monitoring.

Author Contributions

Conceptualization, Y.Z. (Yu Zhang), Y.L., Y.C., and X.W.; methodology, Y.C.; software, Y.Z. (Yu Zhang); Y.Z. (Yu Zhang); validation, Y.C., X.W. and L.Z.; formal analysis, L.Z.; investigation, Y.Z. (Yu Zhang); resources, L.Z.; writing—original draft preparation, Y.Z. (Yu Zhang); writing—review and editing, Y.Z. (Yu Zhang); visualization, Y.Z. (Yuxin Zhang); supervision, Y.Z. (Yu Zhang) and Y.Z. (Yuxin Zhang); project administration, Y.Z. (Yu Zhang); funding acquisition, Y.Z. (Yu Zhang). All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created.

Conflicts of Interest

The authors declare no conflict of interest.

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