

Laboratory study on the effects of environmental temperature and soil moisture content on soil surface radon exhalation rate

Jiaxin Li

Hengyang Normal University

Jiulin Wu

Hengyang Normal University

Yuxi Xie

Hengyang Normal University

Zhongkai Fan

Hengyang Normal University

Ruomei Xie

Hengyang Normal University

Haoyu You

Hengyang Normal University

Hongzhi Yuan

Hengyang Normal University

Yanliang Tan

hytyl@163.com

Hengyang Normal University

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Title page

Names of the authors:

Jiaxin Li¹, Jiulin Wu¹, Yuxi Xie¹, Zhongkai Fan¹, Ruomei Xie¹, Haoyu You¹, Hongzhi Yuan¹,
Yanliang Tan^{1*}

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Affiliation(s) and address(es) of the author(s):

¹ College of Physics and Electronic Engineering, Hengyang Normal University, Hengyang,
Hunan Province 421002, China

E-mail address of the corresponding author:

*Corresponding author: Yanliang Tan

E-mail address: hytyl@163.com

Present address: Hengyang Normal University, Hengyang, Hunan Province 421002, China

Article Highlights:

1. Radon exhalation drops as soil moisture content climbs from 40% to 45%, but rises significantly alongside environmental temperature increases (26°C–31°C).
2. Within these ranges, soil moisture exerts an inhibitory effect 2.5 times stronger than ambient temperature, although elevated heat significantly mitigates this inhibition.
3. Quantifying these dynamics improves accuracy in assessing radon exposure risks under similar conditions.

25 **Authorship Contribution**

26 **Jiaxin Li:** Conceptualization, Methodology, Formal analysis, Writing - original draft,
27 Writing - review & editing, Validation.

28 **Jiulin Wu:** Methodology, Writing - review & editing.

29 **Yuxi Xie:** Validation.

30 **Zhongkai Fan:** Writing - review & editing.

31 **Ruomei Xie:** Formal analysis.

32 **Haoyu You:** Validation, Formal analysis.

33 **Hongzhi Yuan:** Supervision, Validation.

34 **Yanliang Tan:** Conceptualization, Methodology, Resources, Supervision, Validation.

35

Laboratory study on the effects of environmental temperature and soil moisture content on soil surface radon exhalation rate

Jiaxin Li¹, Jiulin Wu¹, Yuxi Xie¹, Zhongkai Fan¹, Ruomei Xie¹, Haoyu You¹, Hongzhi Yuan¹, Yanliang Tan^{1*}

¹ College of Physics and Electronic Engineering, Hengyang Normal University, Hengyang, Hunan Province 421002, China

Abstract

This study investigates the combined effects of environmental temperature (26°C–31°C) and soil moisture content (40%–45%) on the soil radon exhalation rate. By using a controlled laboratory simulation to minimize outdoor field interferences, this research precisely isolates and quantifies the independent and synergistic impacts of these variables. Results reveal that moisture is the dominant inhibitory factor, while temperature strongly promotes radon exhalation. Furthermore, elevated temperatures significantly alleviate the inhibitory effect of soil moisture. This novel quantification provides an accurate reference basis for assessing how environmental parameter combinations dynamically govern radon risk.

Keywords: Radon exhalation rate; Soil moisture content; Environmental temperature; Interaction effect

1. Introduction

Radon (^{222}Rn), as an important source of ionizing radiation, has been proven to be a hazardous factor. The risk of radon exposure faced by humans in their residences and workplaces is particularly significant [1]. According to global health authorities, radon ranks right behind smoking as the leading driver of pulmonary malignancies worldwide. Consequently, this environmental hazard has become a major focal point in numerous epidemiological investigations regarding public well-being [2]. Regarding its nuclear characteristics, radon functions as a noble gas with an atomic number of 86. It emerges from the radioactive breakdown of Ra-226, a process that occurs within the broader U-238 decay cascade. It is also the gas with the highest known density, with a density approximately 7.5 times that of air. In the natural environment, radon exists in various isotopic forms. With a decay period spanning 3.8 days, Rn-222 stands out as the most enduring and prevalent variant among all isotopes of this element. After being released from the bedrock, radon is driven by various diffusion effects such as pressure changes and temperature fluctuations. It will migrate through the microscopic and meso-porous and fissured spaces within the soil and rocks, following the concentration gradient, and eventually enter the interior of the building. Studies reveal that the radon originating from the soil beneath buildings is the primary source of indoor air radon. [3].

It is worth noting that radon will further decay into a series of short-lived solid radioactive isotopes. The radiation release rates of these daughter elements are even faster, and they pose a greater potential threat to health than radon itself. Among the decay products of radon, the alpha-emitting isotopes polonium (^{218}Po) and lead (^{214}Pb) are the main contributors to the radiation dose from radon exposure, accounting for over 90% of the total. These nuclides have

the potential to harm respiratory epithelial cells and DNA. Injuries to respiratory epithelium can trigger pulmonary illnesses linked to this noble gas, and chronic inhalation may elevate a person's susceptibility to pulmonary malignancies. Furthermore, because this element emits radiation while remaining entirely invisible, tasteless, and scentless, quantifying its ambient levels requires specialized monitoring equipment. As the primary source of background radiation exposure in the environment, radon accounts for 55% of the total contribution, and its concentration varies significantly in different regions and even during different seasons [4]. In indoor environments, due to the continuous accumulation of radon decay products, the concentration may reach levels that are harmful to health. Climate change is believed to potentially intensify the process of radon migration into indoor spaces, thereby increasing health risks. According to epidemiological data, a 100 Bq m⁻³ increase in indoor radon levels is linked to a roughly 16% higher risk of lung cancer. Reducing radon exposure levels is expected to prevent 35% to 40% of radon-related lung cancer cases [5]. Studies in recent years have proposed a potential association between radon exposure and heart diseases. This finding further highlights the comprehensive impact of radon on public health [6].

Since soil acts as the predominant source of indoor radioactive gas, understanding how the radon exhalation rate fluctuates across the topsoil remains crucial for managing interior exposure levels [7]. The study by Wu et al. utilized a rectangular device to replicate radon diffusion in natural soil and beneath concrete surfaces, examining the connection between radon concentration distribution in the soil and the rate of radon exhalation. [8]. While previous literature has investigated how variables including soil moisture content and environmental temperature impact radon exhalation, empirical approaches vary. As an illustration, Yang and

colleagues formulated an analytical framework based on comprehensive field data. Their equation connects the emission dynamics to soil moisture content, atmospheric and subterranean temperature, barometric readings, and autocorrelative features of the flux. [9]. Most existing studies are conducted outdoors. During experiments, in addition to variations in soil moisture content and ambient temperature, environmental vibration, air pressure fluctuations, rainfall and other factors can interfere with the radon exhalation rate. Therefore, how to effectively reduce the influence of other environmental parameters is of great significance for accurately evaluating the combined effect of soil moisture and ambient temperature on the radon exhalation rate.

To overcome the limitations of existing research in quantification accuracy and interaction effect analysis, this study will introduce a WLS model with interaction terms as the core analytical tool. This model can not only effectively address potential heteroscedasticity among variables, enhancing the accuracy of parameter estimation, but also systematically quantify the independent effects and synergistic mechanisms of temperature and moisture content by incorporating temperature–moisture content interaction terms. Simultaneously, it combines Spearman rank correlation analysis to clarify variable association characteristics and validates coefficient stability through ridge regression modeling. In this study, a rectangular prism device was employed to model radon diffusion in soil. Throughout the experiment, variations in radon concentration, environmental temperature, and soil moisture content were recorded. Furthermore, a quantitative study was performed to evaluate how environmental temperature and soil moisture content affect the rate of radon exhalation.

2. Experimental

2.1 Experimental setup and instruments

Prior to the experimental phase, the RAD7 radon detector was calibrated utilizing the official radon baseline facility housed within the University of South China. [10,11]. To guarantee sustained precision alongside consistent operational performance, this device is subjected to a regular biennial calibration schedule. Inside the baseline enclosure, radon activity levels were tracked without interruption utilizing the AlphaGUARD PQ2000 PRO system. Every year, this specific tracking device earns certification from China's National Institute of Metrology, ensuring strict compliance with state measurement guidelines. Consequently, the radioactive gas levels within the University of South China's calibration facility possess a fully reliable measurement tracing pathway, establishing a highly exact foundation for tuning the RAD7 equipment. To compute the adjustment multiplier, we divide the certified gas baseline by the sensor's registered output. Throughout this verification phase, our RAD7 unit resided inside a controlled Rn-222 enclosure to ensure steady ambient radioactive conditions. Total system capacity—covering all hoses, the desiccator, and the purifying mesh—equaled 550 mL, operating alongside a circulation speed of 0.7 liters per minute. Data collection then proceeded across multiple gas intensity tiers. For each set of five consecutive measurements, the average measured concentration was calculated, and its ratio to the corresponding reference radon concentration was taken as the calibration factor for that set. The overall calibration factor was obtained by averaging the calibration factors from all sets. The specific results are summarized in Table 1, ultimately determining the calibration factor to be 1.08 ± 0.01 . All radon concentration data utilized in this study represent the actual values obtained after applying the calibration factor.

Table 1 A summary of average RAD7 readouts ($\pm 2\sigma$), standard reference averages, and the computed correction ratios ($\pm 1\sigma$)

NO.	Mean RAD7 Readouts (per 5-measurement batch) (Bq m^{-3})	Mean Reference Data (per 5-batch set) (Bq m^{-3})	Corresponding Calibration Factor
1	3476 ± 200	3760	1.08 ± 0.01
2	2708 ± 177	2931	1.08 ± 0.01

The study took place at the Radiation Laboratory of Hengyang Normal University. A rectangular prism apparatus was used for replicating the transport of radon gas within natural soil. The physical model features a square base of 0.5 m by 0.5 m, coupled with a total height of 2.0 m. Its upper section is surrounded by sheet metal, and the actual area in contact with the atmosphere spanning $0.42 \text{ m} \times 0.42 \text{ m}$. Fig. 1 illustrates this physical configuration.



Fig. 1 Physical diagram of the rectangular prism soil column simulation apparatus and radon accumulation chamber connection

Radon diffusion in soil follows Fick's law. In a one-dimensional steady state, focusing solely on radon diffusion in a uniform soil medium, the differential equation for vertical radon diffusion in soil is established. [12]:

$$D_e \frac{dc^2(x)}{dx^2} - \lambda c(x) + \frac{A}{\eta} = 0 \quad (1)$$

In this formula, D_e stands for the radon effective diffusion coefficient (expressed in $\text{m}^2 \text{s}^{-1}$). The term $c(x)$ indicates the gas activity concentration at a specific underground distance x (in Bq m^{-3}), with x representing the vertical penetration in meters. Furthermore, λ defines the radioactive decay constant for this isotope (equaling $2.1 \times 10^{-6} \text{ s}^{-1}$), η refers to the porosity of the medium, and A describes the continuous generation flux of this noble gas within the earth matrix ($\text{Bq m}^{-3} \text{s}^{-1}$).

Given that radon accumulation at the ground-air interface drops to negligible levels and is treated as virtually nil, the established mathematical constraint becomes: $c(0)=0$. As the depth of the soil increases indefinitely, the radon concentration does not reach infinity; the boundary condition is: $c(x \rightarrow \infty)=a$, where a is a finite value.

$$c(x) = \frac{\left(1 - e^{-x\sqrt{\frac{\lambda}{D_e}}}\right) A}{\lambda \eta} \quad (2)$$

Consider a metal pipe containing soil that is suspended vertically in the air, with a length of $2h$. We set the system restrictions to $c(0) = 0$ combined with $c(2h) = 0$. Integrating these requirements into Eq. (1) consequently produces Eq. (3).

$$c(x) = \frac{A}{\lambda \eta} \left(\frac{1 - e^{-x\sqrt{\frac{\lambda}{D_e}}} + e^{-2h\sqrt{\frac{\lambda}{D_e}}} - e^{x\sqrt{\frac{\lambda}{D_e}} - 2h\sqrt{\frac{\lambda}{D_e}}}}{1 + e^{-2h\sqrt{\frac{\lambda}{D_e}}}} \right) \quad (3)$$

At $x = h$, $c(x)$ achieves its peak value. By positioning a metallic barrier at this exact location, the area situated directly overhead serves as the physical testing apparatus. At vertical depths not exceeding h , the transport of this radioactive gas adheres strictly to the formulated

mathematical framework. Since the value of e^{-4} is approximately 0.0183, $\sqrt{\frac{\lambda}{D_e}}$ approaches 1

and $e^{-2h\sqrt{\frac{\lambda}{D_e}}}$ approaches 0. Under these conditions, Eq. (3) simplifies to Eq. (2), suggesting the current apparatus is capable of simulating one-dimensional vertical radon transport within actual ground conditions.

Before beginning the trials, indoor temperature was stabilized at 30 degrees Celsius via an air-conditioning unit. Following this, water was introduced to the upper section of the setup to replicate how precipitation influences the radon exhalation rate at the ground-air interface. Upon applying this liquid, soil moisture content at the topmost layer of the test medium reached approximately 45%. To determine the radon exhalation rate from the highest level of the equipment, a specialized radon accumulation chamber was utilized. Constituting a rectangular prism, this specific tool possesses spatial parameters of 30, 20, and 10 centimeters for its longitudinal, lateral, and vertical axes, respectively. Operationally, it was pushed 2 cm downward into the superficial earth layer capping the device. A soil moisture detector and a temperature/humidity sensor were placed inside the chamber to record changes in soil moisture content and environmental temperature and humidity during the experiment. To ensure consistency between the measurement data and the radon concentration data, the measurement intervals for the soil moisture detector and the temperature/humidity sensor were set to match those of the RAD7 instrument.

Fitted on the chamber's ceiling are entry and exit valves linked directly to the RAD7 detector. By utilizing alpha spectroscopy, the monitor logs the activity concentration of the radioactive gas along with its progeny, offering a measurement capacity stretching from 4 up to 750,000 Bq m⁻³ alongside an error margin of 2σ. At the beginning of the experiment, the

RAD7 was connected to a power supply to prevent data loss of recorded radon concentration values due to insufficient battery power during the experiment. The instrument was set to "sniff mode" with a sampling cycle of 10 minutes, and it operated continuously for approximately 10 days, ultimately recording 1,357 sets of valid radon concentration data.

2.2 Calculation of radon exhalation rate

The temporal variation pattern of ^{218}Po concentration inside the radon accumulation chamber conforms to Eq. (4) [13].

$$C_{po}(t) = \frac{JS \left[\lambda_e \left(1 - e^{-\lambda_{po}t} \right) - \lambda_{po} \left(1 - e^{-\lambda_e t} \right) \right]}{\lambda_e V (\lambda_e - \lambda_{po})} \quad (4)$$

Within this equation, $C_{po}(t)$ indicates the ^{218}Po activity level (expressed in Bq m^{-3}) at a given moment t , acting as the empirical reading logged by the RAD7 monitor. The parameter J denotes the radon exhalation rate (measured in $\text{Bq m}^{-2} \text{s}^{-1}$), while S signifies the base area of the radon accumulation chamber (0.06 m^2). Furthermore, λ_e represents the aggregate attenuation factor (s^{-1}), integrating the natural disintegration rate, the reverse diffusion parameter, alongside the system's seepage metric. λ_{po} defines the specific disintegration parameter for ^{218}Po (equating to $3.78 \times 10^{-3} \text{ s}^{-1}$). V is the total system volume (0.0062 m^3), including the radon accumulation chamber, drying tube, internal chamber of the RAD7, and connecting tubing; and t is the measurement time (s).

Utilizing the Origin 2025 platform, we applied a non-linear curve-fitting approach adopting Eq. (4) to the first 24 groups of radon concentration readings, thereby extracting the effective decay constant λ_e . When t is 240 minutes, $e^{-\lambda_{po}t}$ is approximately 2.3×10^{-24} , which is

infinitely close to 0. Consequently, the mathematical expression of Eq. (4) is streamlined to yield Eq. (5).

$$c_{po}(t) = \frac{JS}{\lambda_e V} \quad (5)$$

Through this procedure, we determine radon exhalation rate J utilizing the expression formulated in Eq. (6).

$$J = \frac{c_{po}(t)\lambda_e V}{S} \quad (6)$$

Since the effective decay constant exhibits minimal variation throughout the entire experiment, the value obtained by fitting the first 24 sets of radon concentration data can be used as the effective decay constant for the entire experiment. As deduced from Eq. (6), subsequent to a 240-minute duration, a definitive correlation forms, linking radon exhalation rate with environmental temperature plus soil moisture content.

2.3 Model construction

A non-parametric Spearman rank correlation analysis was employed to investigate the association characteristics among variables. This correlation metric is confined within the interval of $[-1, 1]$. A magnitude approaching unity reflects a more robust association, with positive or negative signs dictating whether the variables shift in the same or opposite directions. A WLS model featuring interaction terms was constructed to evaluate how the independent factors, along with the synergistic dynamics involving environmental temperature as well as soil moisture content, influence the radon exhalation rate. Finally, a ridge regression model with

interaction terms was built to verify coefficient stability and assess the impact of multicollinearity.

The WLS model with interaction terms was expressed as shown in Eq. (7):

$$J = \beta_0 + \beta_1 \cdot T_{center} + \beta_2 \cdot M_{center} + \beta_3 \cdot (T_{center} \times M_{center}) \quad (7)$$

Herein, the variable J corresponds to the radon exhalation rate escaping across the uppermost earth layer; β_0 is the constant term, representing the baseline level of the exhalation rate; β_1 is the main effect coefficient for the centered temperature, characterizing the independent influence of temperature on the radon exhalation rate—a positive coefficient indicates that rising temperature promotes radon exhalation; β_2 acts as the primary effect coefficient for the centered moisture variable, quantifying the isolated impact exerted by soil moisture content upon the radon exhalation rate—a negative coefficient indicates that increasing moisture content inhibits radon exhalation; β_3 is the coefficient for the temperature–moisture content interaction term, characterizing their synergistic influence—a positive coefficient suggests that high temperature alleviates the inhibitory effect of moisture content; T_{center} is the centered value of environmental temperature; M_{center} is the centered value of soil moisture content; and $T_{center} \times M_{center}$ is the interaction term between the centered temperature and centered moisture content, used to capture the synergistic effect of temperature and moisture content.

The ridge regression model with interaction terms is expressed as shown in Eq. (8).

$$\min_{\beta} \sum_{i=1}^n \left[J_i - \left(\beta_0 + \beta_1 T_{center,i} + \beta_2 M_{center,i} + \beta_3 (T_{center,i} \times M_{center,i}) \right) \right]^2 + \alpha \sum_{j=1}^3 \beta_j^2 \quad (8)$$

where $\min_{\beta}$ denotes the optimization objective of minimizing the weighted residual sum of squares; n is the effective sample size; $\alpha = 1.0$ is the L2 regularization penalty coefficient, determined via 5-fold cross-validation; $\sum_{j=1}^3 \beta_j^2$ represents the L2 penalty term on the regression coefficients; and all other symbols are consistent with those in the WLS model.

3. Results and discussion

3.1 Results

Using Origin 2025 software, the first 24 sets of data were fitted, as depicted in Fig. 2. Here, the horizontal axis represents time, and the vertical axis represents radon concentration. The red curve depicts the theoretical prediction of the model, the black squares are the experimentally measured radon concentration data points, and the black vertical lines are error bars, representing the uncertainty of the concentration measurement at each time point. The fitting yielded an effective decay constant $\lambda_e = 4.49675 \pm 0.995488 \times 10^{-4} \text{ s}^{-1}$ and an initial radon exhalation rate $J_0 = 19.21 \pm 3.61 \text{ mBq m}^{-2} \text{ s}^{-1}$.

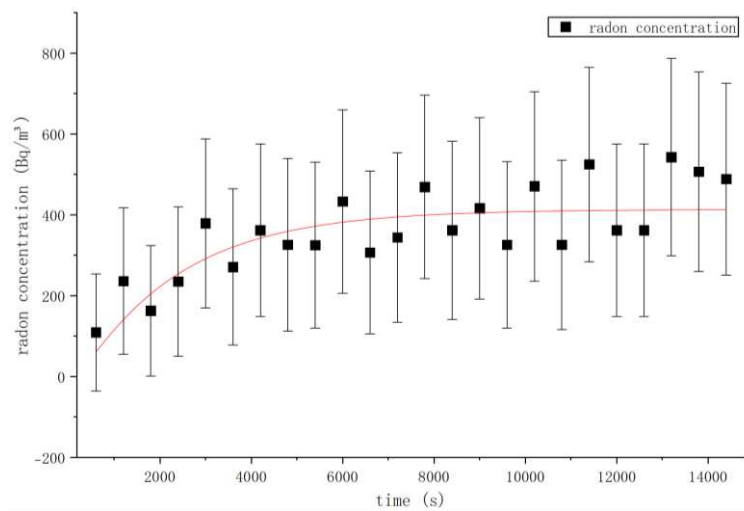


Fig. 2 The first 24 sets of radon concentration data and the nonlinear fitting curve (the red curve represents the theoretical predictions, the black squares denote the measured values, and the error bars indicate the 2σ uncertainty)

Subsequent 1333 sets of data were processed using Eq. (6) to calculate the corresponding radon exhalation rates. Due to the large volume of the room, the considerable distance between the simulation apparatus and the air conditioner, and the influence of external diurnal temperature fluctuations on the indoor temperature, the temperature at the soil surface exhibited an overall gradual upward trend. Concurrently, the soil moisture content showed an overall declining trend due to evaporation. As the environmental humidity remained essentially constant throughout the experiment, its influence on the radon exhalation rate could be neglected. The temporal variation curves of these parameters are plotted in Fig. 3, where the horizontal axis represents time. Plotted against the left vertical axis is the radon exhalation rate (indicated by the black trace). Conversely, the right vertical axis serves as the scale for the soil moisture content (illustrated in red) alongside the environmental temperature (depicted in blue).

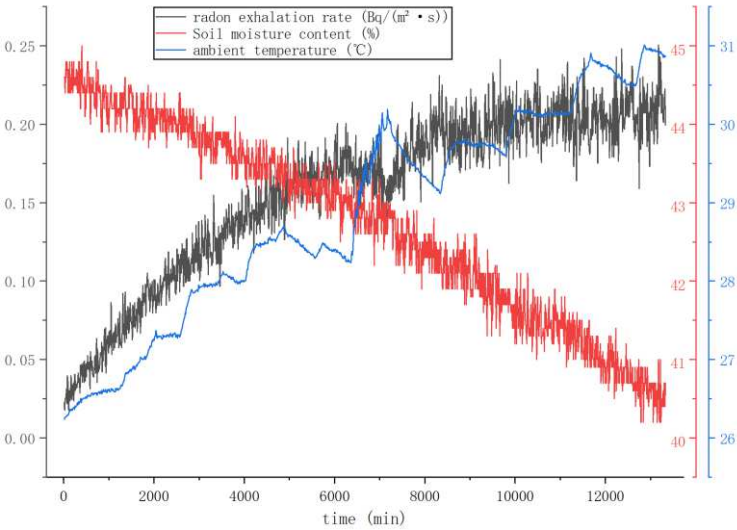


Fig. 3 Time-dependent profiles illustrating the radon exhalation rate alongside the soil

moisture content, as well as the environmental temperature, across the following 1333 data records

3.2 Discussion

A Spearman framework was utilized to determine the degree to which the radon exhalation rate responds to environmental temperature as well as soil moisture content. The correlation results revealed that there were highly significant monotonic associations among all variables ($p < 0.001$). The correlation heatmap is shown in Fig. 4. A robust positive association linking environmental temperature with the radon exhalation rate is evident ($r = 0.8829$), indicating that an increase in environmental temperature significantly promotes radon exhalation from the soil surface. A strong negative correlation is observed between soil moisture content and the radon exhalation rate ($r = -0.9138$), with an association strength greater than that of temperature, suggesting that soil moisture content is a key factor inhibiting radon exhalation. A highly significant negative correlation exists between environmental temperature and soil moisture content ($r = -0.9596$), which objectively reflects the physical phenomenon of "increasing temperature leading to soil moisture evaporation" during the experiment. Analyzing single-variable dynamics, radon exhalation rate exhibits a clear linear dependence on soil moisture content. Specifically, as soil moisture content climbed from 40% up to 45%, radon exhalation rate steadily dropped from $232.1 \text{ mBq m}^{-2} \text{ s}^{-1}$ down to $16.4 \text{ mBq m}^{-2} \text{ s}^{-1}$. This observation firmly validates the established gas migration theory of "moisture filling pores and enhancing adsorption." In contrast, the impact of environmental temperature upon radon exhalation rate displays a notable linear relationship. As environmental temperature escalated from 26°C to

31 °C, the radon exhalation rate surged from 16.4 mBq m⁻² s⁻¹ to 232.1 mBq m⁻² s⁻¹. This phenomenon highlights how thermodynamics govern molecular kinetic activity and diffusion parameters for this radioactive gas.

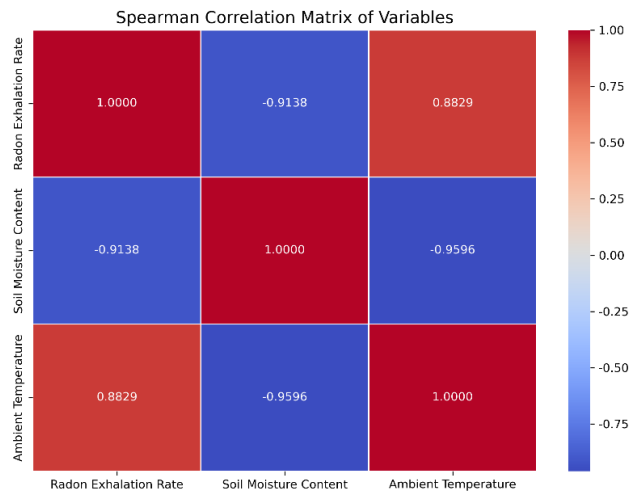


Fig. 4 Heatmap of Spearman rank correlation coefficients among variables ($p < 0.001$)

To evaluate the respective impacts of environmental temperature alongside soil moisture content regarding the radon exhalation rate, we employed both a WLS framework and a Ridge Regression approach, each incorporating interaction variables. The corresponding analytical findings are summarized within Table 2.

Table 2 Analysis results of the WLS model with interaction terms and the Ridge

Regression model with interaction terms

Model Type	R ²	Adjusted R ²	temperature coefficient (β_1)	Moisture content coefficient (β_2)	Interaction term coefficient (β_3)
Weighted Least Squares	0.9150	0.9148	0.013485	-0.033772	0.020485
Ridge Regression	0.9150	0.9148	0.013861	-0.033420	0.020328

The fitting results of the WLS model with interaction terms show that the temperature main effect coefficient is $\beta_1 = 0.013485$, the moisture content main effect coefficient is $\beta_2 = -0.033772$, and the interaction effect coefficient is $\beta_3 = 0.020485$. The goodness-of-fit is indicated by an $R^2 = 0.9150$ and an adjusted $R^2 = 0.9148$, demonstrating that this model explains approximately 91.48% of the variation in the radon exhalation rate, which reflects a favorable fitting performance.

After constructing the WLS model, it is necessary to verify whether core independent variables exhibit multicollinearity. Multicollinearity may lead to unstable coefficient estimates, threatening the reliability of the WLS model. The research employs the Variance Inflation Factor (VIF) as a diagnostic measure to determine the level of redundant associations among independent variables. The calculation formula for VIF is shown in Eq. (9).

$$VIF_i = \frac{1}{1 - R_i^2} \quad (9)$$

In the formula: R_i^2 acts as the determinative metric for predicting variable i utilizing the remaining input parameters. Evaluation benchmarks dictate that $VIF < 5$ proves negligible variable overlap; a metric bounding $5 \leq VIF < 10$ demonstrates partial collinearity, whereas observing $VIF \geq 10$ establishes profound multi-collinearity.

A VIF test was conducted on the core independent variables (temperature, moisture content) of the WLS model. The results revealed severe multicollinearity between temperature and moisture content ($VIF = 10.04 > 10$). To further verify whether this multicollinearity substantially interfered with the coefficient estimation of the WLS model, a ridge regression model was constructed to mitigate multicollinearity. A comparative analysis with the WLS

model showed that: the coefficients for all variables in both models were highly consistent, with differences less than 5%, and the coefficient signs were identical. The goodness-of-fit was also identical, with both the ordinary R^2 and adjusted R^2 being 0.9150 and 0.9148, respectively, indicating no difference in explanatory power for the variation in radon exhalation rate. Although ridge regression significantly alleviated multicollinearity (VIF decreased from 10.04 to 4.82), the coefficients showed almost no difference from those of the WLS model. This suggests that the severe multicollinearity in this study did not cause substantial interference with the coefficient estimation of the WLS model.

Hypothesis testing was conducted on the residuals of the WLS model with interaction terms to verify its statistical robustness. The Shapiro–Wilk normality test result showed $p = 0.854$, indicating that the model residuals followed a normal distribution, satisfying the normality assumption of the linear regression model and ensuring the statistical validity of coefficient t-tests and confidence interval estimations. All variable coefficients were significant at the 95% confidence level. The Levene’s test for homogeneity of variance in the WLS model yielded $p = 0.0520$, suggesting that the assumption of variance homogeneity is essentially met, which demonstrates the reliability of the WLS model.

Therefore, it can be concluded that the main effect of temperature is positive. Assuming soil moisture content remains stable, each 1°C elevation regarding environmental temperature causes radon exhalation rate to grow by a mean value of 13.5 mBq m⁻² s⁻¹. This aligns with the positive correlation ($r = 0.8829$) found in the Spearman analysis, reflecting the promoting effect of temperature on the thermal motion of radon molecules. The main effect of moisture content is negative. Assuming environmental temperature remains stable, each 1% elevation regarding

soil moisture content causes the radon exhalation rate to decline by a mean value of 33.8 mBq m⁻² s⁻¹. Its effect strength is 2.5 times that of temperature, verifying that soil moisture content is the dominant inhibitory factor for radon exhalation. The positive interaction metric (0.0205) reveals a profound synergistic dynamic involving both parameters regarding radon exhalation rate. Specifically, during periods of elevated environmental temperature, the suppressive impact exerted by soil moisture content upon radon exhalation rate becomes noticeably mitigated. The underlying physical mechanism is that high temperatures reduce the adhesion of soil moisture. Even at higher moisture levels, it becomes difficult for water in the soil pores to form a continuous sealing layer, thus still allowing pathways for radon diffusion. Consequently, the "pore-blocking effect" associated with increased moisture content is weakened under elevated temperatures.

The results of this study align closely with traditional radon migration theory and support the conclusions of recent related studies. As an example, the Rayleigh model applied by Yang et al. to characterize the functional dependence of the radon exhalation rate upon soil moisture content takes the form of Eq. (10) [9].

$$R(w) = E(w) = \frac{bwe^{\frac{1}{2}\left(1-\frac{w^2}{c^2}\right)}}{c} \quad (10)$$

Based on Eq. (10) and the findings of Yang et al., Fig. 5 illustrates the functional dependence of the radon exhalation rate on soil moisture content. It can be seen that the radon exhalation rate reaches a maximum when soil moisture content reaches 10%. As the moisture content continues to increase, the radon exhalation rate gradually declines. This trend aligns

perfectly with the empirical findings, demonstrating how a drop in soil moisture content directly drives a progressive escalation of the radon exhalation rate at the soil surface.

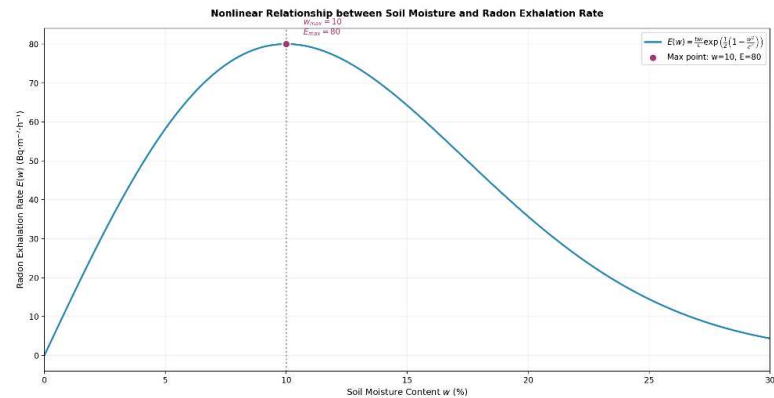


Fig. 5 The correlative trajectory for the radon exhalation rate versus soil moisture content is dictated according to Eq. (10)

Since the entire experiment had already run for 10 days and the soil column volume was large, variations involving the soil moisture content were slow. To reduce the moisture content to around 10% would likely require one year or even longer. Therefore, the experiment was not continued to observe the variation in the radon exhalation rate with changes in soil moisture content.

This study is the first to quantitatively assess the independent and interactive effect strengths of temperature and moisture content through this model in a rectangular prism soil column simulation experiment. From the perspective of classical radon migration theory, radon exhalation from soil is governed by a "diffusion–adsorption" equilibrium. Temperature alters the diffusion coefficient by affecting molecular thermal motion, while moisture content affects diffusion pathways and adsorption capacity by modifying the pore structure. The strong negative correlation ($r = -0.9596$) observed in the experiment between temperature and

moisture content reflects the typical characteristic in natural environments of "temperature increase → enhanced soil evaporation → decreased moisture content." This also sheds light on the typical occurrence at actual sites where the rate of radon exhalation markedly rises under conditions of high temperature and dryness.

This study has certain limitations, as the experiment was conducted under conditions of a single soil type and fixed compaction level. Future research could expand to multifactorial experiments incorporating different soil physicochemical properties (e.g., porosity, organic matter content) to refine the predictive model.

4. Conclusion

Based on 10 days of continuous monitoring and data analysis, this study draws the following conclusions: Under conditions of soil moisture content ranging from 40% to 45% and environmental temperature ranging from 26 to 31 °C, the rate of radon exhalation from the soil surface is mainly influenced by the moisture content. It exhibits a very strong negative correlation with moisture content ($r = -0.9138$) and a very strong positive correlation with environmental temperature ($r = 0.8829$). Quantitative assessments demonstrate that a 1 °C rise regarding environmental temperature elevates radon exhalation rate by a mean value of 13.5 mBq m⁻² s⁻¹. Conversely, each 1% upward shift regarding soil moisture content lowers radon exhalation rate by a mean value of 33.8 mBq m⁻² s⁻¹, confirming that soil moisture content exerts a regulatory force 2.5 times stronger than the thermal impact generated by environmental temperature. Furthermore, a significant interaction exists between these parameters: elevated environmental temperature prominently weakens the inhibitory effect exerted by soil moisture content upon radon exhalation rate. This study provides a valuable conceptual reference for

418 accurately assessing the impacts of these two variables on the radon exhalation rate, and offers
419 support for future research on the effects of different combinations of environmental parameters
420 on radon exhalation. Furthermore, it is of great significance for more accurate assessment of
421 soil radon risk.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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