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Classroom Radon Exposure and Pulmonary Function Among South African Primary School Children

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Highlights

What are the main findings?

- Radon concentrations in classrooms varied in some primary schools in the Eastern Cape, South Africa, with higher levels observed at sites near mining areas.
- An inverse association between radon concentration and FEV_1/FVC was observed after adjustment for age, height, weight, and gender. However, this association was essentially absent after excluding Site B. No significant associations were observed with FEV_1 or FVC.

What are the implications of the main findings?

- The findings do not demonstrate a consistent independent association between classroom radon exposure and pulmonary function in this cohort, and they indicate substantial heterogeneity across sites.
- School-based radon monitoring, particularly in areas associated with mining, and longitudinal studies incorporating residential exposure, respiratory symptoms, and repeated assessments of lung function are needed.

Abstract

Background: The aim of the study is to evaluate the relationship between indoor radon exposure among schoolchildren and pulmonary function while adjusting for demographic characteristics in the Province of Eastern Cape, South Africa. **Methods:** A cross-sectional study was conducted across 16 primary schools grouped into four site categories by mining proximity. Classroom radon was measured with calibrated AlphaE electronic radon monitors over 62 days. Spirometry (FEV_1, FVC, FEV_1/FVC) was performed in 512 children aged 6–12 years. Associations between radon concentration and each spirometric outcome were estimated using multivariable linear regression across three sequential models. **Results:** Mean classroom radon concentration was 320 ± 10.51 Bq/m^3, highest in the schools near the defunct mine/quarry (257 ± 29.0 Bq/m^3) and lowest in reference schools not near any mine (62 ± 8.2 Bq/m^3). In the fully adjusted model, radon concentration was minimally significantly and inversely associated with FEV_1/FVC (B = −0.103 percentage points per 100 Bq/m^3, 95% CI: −0.154 to −0.054, $p < 0.001$), while no significant association was observed with FEV_1 or FVC. However, in a sensitivity analysis excluding Site B, the association between radon concentration and FEV_1/FVC was essentially null (B ≈ −0.00001, $p = 0.960$). The previously observed between-site difference in FEV_1/FVC was no longer statistically significant in the fully adjusted comparison among Sites A, C, and D. **Conclusions:** The study identified differences in indoor radon concentrations across

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schools and a site-specific difference in FEV_1/FVC, with the lowest ratio observed at Site B, which also had one of the highest mean radon concentrations. The apparent inverse association between radon concentration and FEV_1/FVC observed in the pooled analysis was not maintained after adjustment for study sites and was essentially eliminated when Site B was excluded. Given the cross-sectional design and classroom-level exposure, these findings are hypothesis-generating and support prioritising indoor radon screening in schools near mining activity pending confirmation in studies using individual dosimetry and longitudinal follow-up.

Keywords: radon; lung function; spirometry; FEV1; FVC; FEV1/FVC ratio

1. Introduction

Radon (222Rn) is a colourless, odourless, naturally occurring radioactive noble gas formed by the decay of radium (226Ra) within the uranium (238U) decay series [1,2]. The gas is released from soil, rock, and groundwater and accumulates in enclosed spaces with limited ventilation, including classrooms situated above radon-permeable geology [3,4]. Radon decays into its short-lived progenies (Polonium, 218Po; Lead 214Pb; Bismuth, 214Bi; and Polonium, 214Po), releasing α and β particles and γ radiation. Upon inhalation, the alpha particles are deposited on the bronchial epithelium. They then irradiate basal and secretory cells to generate reactive oxygen radicals, provoke localised inflammatory responses, and potentially cause mutagenic changes or cellular necrosis [5,6].

The International Agency for Research on Cancer (IARC) designates radon as a Group 1 human carcinogen based on consistent evidence, ranking radon as the second most significant cause of lung cancer globally, subsequent to tobacco smoking [7–10]. A pooled analysis of European case–control studies established a linear, no-threshold dose–response relationship between residential radon exposure and lung cancer risk, with an approximate 16% increase in risk per 100 Bq/m^3 increment [11]. The World Health Organization (WHO) advocates for a reference level of 100–300 Bq/m^3 in indoor environments [12,13], whereas various national authorities, including the United States Environmental Protection Agency, define an action level of 148 Bq/m^3 (4 pCi/L) [14–16].

Beyond its established mutagenic potential, a growing body of evidence suggests that radon progenies may also elicit non-malignant respiratory malfunction through oxidative and inflammatory mechanisms distinct from genotoxic carcinogenesis [17–19]. Alpha-particle bombardment of airway epithelium has been shown experimentally to induce cytokine release, including interleukin-6, interleukin-8, and tumour necrosis factor-alpha, as well as structural remodelling of small airways [20–22]. These processes could plausibly manifest as measurable changes in ventilatory mechanics, including reductions in forced expiratory volume in 1 s (FEV1), forced vital capacity (FVC), or the FEV1/FVC ratio—the spirometric indices often used to characterise obstructive and restrictive ventilatory pathologies [23–26].

Compared to adults, children are more susceptible to radon-associated respiratory effects due to their developing respiratory systems and higher minute ventilation per unit body mass, which results in a proportionally greater deposition of radon progeny per unit airway surface area [27,28]. Additionally, children's airways are narrower and continue to grow actively throughout the first decade of life, a developmental stage during which environmental insults may have disproportionate or lasting impacts on the trajectory of adult lung function [29]. Furthermore, children in primary education typically spend six to eight hours daily within school buildings, suggesting that radon exposure in

educational environments may constitute a significant portion of their total daily radon dose, independent of residential exposure [30–32].

Mining activity is a well-documented source of elevated environmental radon, both through the direct disturbance and exposure of uranium- and radium-bearing host rock and through deposition of waste rock particles with elevated natural radioactivity [33–35]. Communities situated near mining operations may therefore experience elevated ambient and indoor radon concentrations relative to populations situated farther from such geological radon sources. South Africa has a long history of mining activity, including gold, coal, and, more recently, mineral sands and rare-earth element extraction, where geological formations with elevated natural radioactivity have been documented [36–38]. Despite this context, published data on indoor radon concentrations in South African schools and their relationship to children's respiratory health remain scarcely evaluated.

The existing paediatric literature on radon and lung function beyond the African continent is also limited, and where data exist, it primarily focuses on pathological conditions. In the School Inner City Asthma Study conducted in the United States, high-dose exposure to radon decay products was significantly correlated with a reduced FEV1/FVC ratio [39]. This suggests that exposure to radon progeny independently causes localised airway inflammation, thereby accentuating the obstructive pattern in children with asthma. In reference to [39], children with asthma who had higher exposure to radon decay products had significantly lower FEV1/FVC z-scores, thereby impairing their lung function [40]. Compared with North American studies [39,40], there is a conspicuous absence of research on school-aged children using direct indoor radon measurements paired with standardised spirometry in the African context. This highlights an important gap in evidence, especially considering the extensive mining activities and the large paediatric populations attending under-resourced schools across much of the South African mining belt.

The primary objective of this study was to evaluate the relationship between indoor radon concentrations measured in primary schools and spirometric lung function parameters, specifically FEV1, FVC, and the FEV1/FVC ratio, among children under 12 years of age in the Province of Eastern Cape, while considering demographic and anthropometric factors such as age, height, weight, and gender.

2. Materials and Methods

2.1. Study Design, Setting, and Site Classification

A cross-sectional epidemiological investigation was conducted in four towns within the Eastern Cape Province of South Africa, selected to represent categories of exposure with approximately equivalent sample sizes. A total of sixteen primary schools were included, with four schools per study site representing each of the four study locations: schools situated within 15 km of active sand mining and quarry operations (Site A), schools located within 15 km of defunct, sand mining sites (Site B), schools within 15 km of proposed riverbed mining explorations (Site C), and reference schools not located within 15 km of prospective metal mining activities (Site D)—a reference location not in direct proximity to metal mining activities, either at present, in the past, or prospectively compared with Sites A, B, and C. This stratified sampling approach aligns with established methodologies for geo-coded assessment of environmental exposure gradients in scenarios where continuous individual dosimetry data are lacking [41,42].

2.2. Study Population

Children enrolled in the participating schools, aged between 6 and 12 years, were eligible for inclusion. A total of 512 children participated, with approximately 32 children recruited per school (128 children per site category). Exclusion criteria applied at the point

of spirometric testing included respiratory illness in the preceding four weeks, a pre-existing diagnosis of asthma or other chronic respiratory condition reported by caregivers/parents, and inability to produce technically acceptable spirometric manoeuvres, despite adequate supervision.

2.3. Indoor (Classroom) Radon Measurement

Indoor radon levels were measured continuously with a calibrated AlphaE portable electronic radon monitor (ERM) (Bertin Technologies SAS, France), a diffusion-chamber instrument with a silicon diode detector, measuring radon in the range of 20 Bq/m^3 to 10 MBq/m^3 with an instrument calibration error of 10% [43]. Measurements were conducted over a period of 62 days during summer/autumn (February to April 2025). Radon concentrations were measured in each classroom during school hours with windows open (occupied, ventilated conditions) and during off-hours with windows closed (unoccupied, closed-building conditions), consistent with approaches used in similar school-based environmental health surveys [44,45]. The exposure metrics used in this study for analysis were the radon concentration during daytime with open windows, which most accurately reflects children's actual exposure, whereas measurements taken during off-hours serve as indicators of radon source strength and are reported separately for other sensitivity analyses. Four AlphaE monitors per study site (one per classroom) were employed across the four study sites.

Furthermore, the AlphaE recorded temperature, relative humidity, and ambient pressure to support data quality and contextual interpretation [46–48]. These environmental factors (Table 1), together with the standard equilibrium factor of 0.4 recorded by the ERMs, were consistently applied in assessing whether the readings represent typical conditions or are affected by transient meteorological phenomena but did not differ meaningfully across the four site categories.

Table 1. Environmental conditions during indoor radon monitoring by study site.

Environmental Parameter	Site A	Site B	Site C	Site D
Temperature (°C), mean ± SD	22.47 ± 2.70	21.76 ± 2.63	22.35 ± 2.69	22.54 ± 2.78
Relative humidity (%), mean ± SD	67.89 ± 4.83	70.87 ± 4.98	68.09 ± 4.59	70.37 ± 5.66
Ambient pressure (mbar), mean ± SD	898.58 ± 14.37	913.97 ± 3.52	1014.83 ± 2.53	897.36 ± 3.43

Radon measurement device (ERM) deployment in this study conformed to established placement guidelines, ensuring units were positioned away from the ceiling, floor, doors, windows, and direct sources of heat [49–51].

2.4. Spirometric Assessment

Spirometry was conducted utilising the MiniSpir handheld spirometer (Medical International Research, Italy) [52], a digital turbine spirometer based on the infrared interruption principle, which offers a volume accuracy of ±2.5% or 50 mL and a flow accuracy of ±5% or 200 mL/s. It complies with the 2025 ATS/ERS Spirometry Guidelines' criteria for acceptability and reproducibility [53–55]. The instrument autonomously performs BTPS (body temperature, pressure, saturated) correction through an internal temperature sensor, accounting for ambient temperature variations within its designated operating range (+10 °C to +40 °C). Testing was carried out at ambient room temperature at the study sites, without the aid of active climate control. Each participant performed at least 3 forced expiratory manoeuvres, with the highest technically valid FEV1 and FVC values recorded for analysis. The FEV1/FVC ratio was calculated as the percentage of FVC expelled within the first second of forced expiration. Spirometric assessments were conducted in a quiet,

designated room at each educational institution during morning hours to minimise diurnal variability and reduce the influence of physical exertion.

2.5. Covariates

Demographic and anthropometric data, including age (years), gender, height (m), and weight (kg), were collected from all participants at the time of testing. Body mass index (BMI, kg/m^2) was subsequently calculated based on height and weight. Additionally, building-related covariates pertinent to indoor air quality—such as building type, basement presence, foundation type, heating system, air conditioning, water supply, smoking exposure, and the timing of building renovations—were obtained through questionnaires. These data aimed to characterise the broader influences on classroom radon exposure at the participating schools, in accordance with established standards in indoor radon epidemiology [56–58], which were consistent across the four study sites.

2.6. Statistical Analysis

Continuous variables are presented as means with standard errors (SE); categorical variables are expressed as frequencies. Variations in baseline demographic and anthropometric characteristics among the four site categories were evaluated using one-way analysis of variance (ANOVA). Similarly, differences in mean indoor radon concentration, FEV1, FVC, and FEV1/FVC across the site categories were assessed by employing one-way ANOVA.

Associations between indoor radon concentration (modelled continuously, scaled by 187 per 100 Bq/m^3 increment for interpretability) and each spirometric outcome (FEV1, FVC, FEV1/FVC) were estimated using multivariable linear regression. Three sequential models were fitted for each outcome: Model 1, an unadjusted (crude) model containing radon concentration alone; Model 2, adjusted for age, height, and weight; and Model 3, fully adjusted for age, height, weight, and gender. Furthermore, a sensitivity analysis was conducted to evaluate the impact of excluding the site with predominantly reduced airway parameters and to assess the overall effects on the remaining three study sites. Pearson and Spearman correlation coefficients were computed to assess the strength and form of bivariate associations between radon concentration and each outcome. All regression coefficients are provided with p-values, with statistical significance indicated at $p < 0.05$.

2.7. Ethical Considerations

Written informed consent was obtained from the parents or legal guardians of all participating children prior to enrolment, and age-appropriate assent was obtained directly from participating children, consistent with international guidance on the ethical conduct of paediatric environmental health research [59–61]. Permission to conduct the study within school premises was obtained from the relevant provincial Department of Education. Participation was entirely voluntary, and parents and children were informed of their right to withdraw from the study at any stage without consequence.

3. Results

3.1. Characteristics of the Study Population

Of the 600 children eligible across 16 schools, 26 did not return parental consent forms, resulting in 574 children enrolled and an overall response rate of 95.7% (ranging from 94.7% to 96.7% across sites; detailed in Table 2). During spirometric assessment, 62 children were excluded: 19 due to acute respiratory illness at testing, 20 because of pre-existing or suspected asthma or respiratory conditions, and 23 for not performing

acceptable spirometric manoeuvres according to ATS/ERS standards, leaving a stratified boot-strapping analytical sample of 512.

Table 2. Participant Distribution.

Site	Eligible	No Consent Returned	Enrolled	Response Rate (%)	Excluded Acute Illness	Excluded: Asthma/Respiratory dx	Excluded: Unacceptable Manoeuvre	Final (*n*)
A	150	8	142	94.7	6	3	5	128
B	150	5	145	96.7	4	5	7	129
C	150	6	144	96.0	7	6	4	127
D	150	7	143	95.3	2	6	7	128
Total	600	26	574	95.7	19	20	23	512

A total of 512 learners participated in the study across the participating schools. The sample comprised 247 boys (48.2%) and 265 girls (51.8%), with a mean age of 8.32 ± 1.71 years (range 6–12 years). Table 3 presents demographic and anthropometric characteristics stratified by site category. Mean age, height, and weight did not differ significantly across the four study sites (all $p > 0.05$), supporting baseline comparability of the exposure groups; however, mean BMI differed modestly but significantly across sites ($p = 0.0015$), with the lowest mean BMI observed in the reference site D.

Table 3. Demographic and anthropometric characteristics of study participants.

Characteristic	Site A	Site B	Site C	Site D	*p*-Value
Age, years (mean ± SD)	8.20 ± 1.71	8.23 ± 1.81	8.47 ± 1.68	8.39 ± 1.66	0.556
Female sex, n (%)	70 (54.7)	61 (47.7)	68 (53.1)	66 (51.6)	0.707
Height, m (mean ± SD)	1.29 ± 0.12	1.29 ± 0.13	1.30 ± 0.11	1.32 ± 0.10	0.100
Weight, kg (mean ± SD)	26.97 ± 5.95	26.56 ± 6.03	28.09 ± 5.66	27.37 ± 5.81	0.192
BMI, kg/m^2 (mean ± SD)	16.01 ± 1.62	15.90 ± 1.82	16.41 ± 1.54	15.56 ± 1.80	0.001

SD: standard deviation; BMI: body mass index. *p*-values.

3.2. Indoor Radon Concentrations by Site Category

The overall mean classroom radon concentration was 320 ± 10.5 Bq/m^3, highest in the schools near the defunct mine/quarry, Site B (257 ± 29 Bq/m^3), and lowest in reference schools not near any mine, Site D (62 ± 8.2 Bq/m^3). The overall distribution of indoor radon concentrations was rightly skewed: the median across all sites was 320 Bq/m^3, with the upper percentiles for Site B increasing to 619 Bq/m^3 at the 75th percentile to a maximum of 882 Bq/m^3 (Figures 1 and 2). Indoor radon concentrations varied across the four site categories. The highest radon concentrations were recorded at Site B (Q3-619 Bq/m^3; interquartile range 458–619 Bq/m^3; maximum 882 Bq/m^3), followed by Site A (Q3-441 Bq/m^3; interquartile range 320–441 Bq/m^3; maximum 886 Bq/m^3. An intermediate concentration was documented at Site C, in proximity to the prospective mine (Q3-468 Bq/m^3; interquartile range 294–468 Bq/m^3; maximum 642 Bq/m^3). The lowest concentrations were noted at Site D, comprising the reference schools distant from metal mines (Q3-206 Bq/m^3; interquartile range 168.5–206.4 Bq/m^3; maximum 338 Bq/m^3), which was the only site whose entire interquartile range fell within the World Health Organization's reference range of 100–300 Bq/m^3.

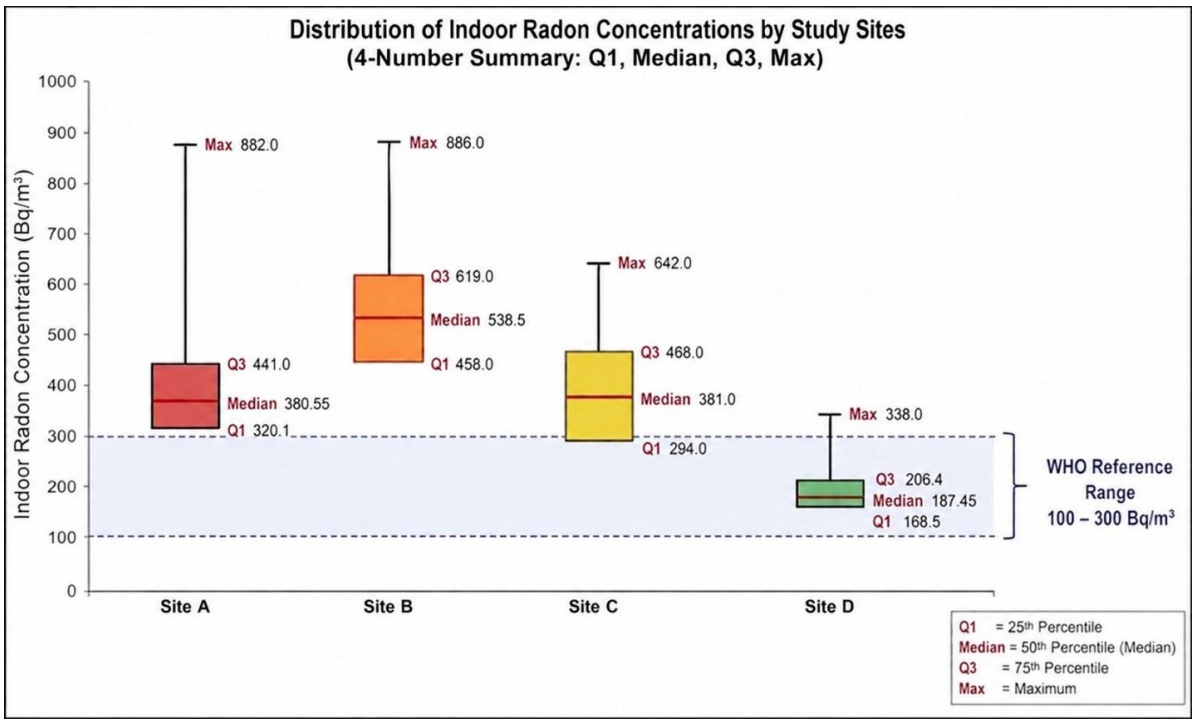

Figure 1. Distribution of Radon Concentrations across Study Sites.

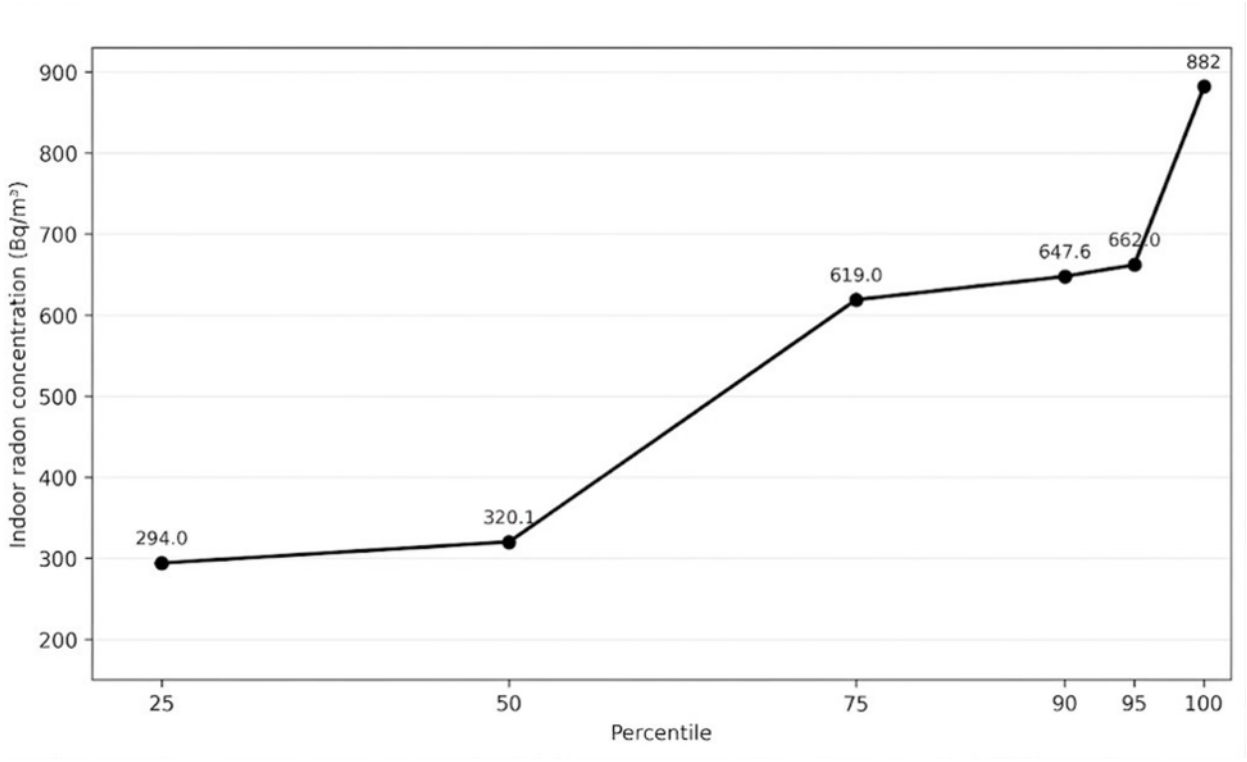

Figure 2. Cumulative Distribution of Indoor Radon Concentrations by Percentile.

3.3. Lung Function Parameters by Site Category

Table 4 presents unadjusted spirometric outcomes by site category. Mean FEV1 and FVC did not differ significantly across the four study sites (FEV1: F = 1.68, $p = 0.171$; FVC: F = 1.50, $p = 0.225$). In contrast, the FEV1/FVC ratio differed significantly across site categories (F = 62.55, $p < 0.001$), with the lowest mean ratio observed among children attending schools near Site B (85.33 ± 1.805%) compared with Site A (87.28 ± 1.527%), Site C (87.52 ± 1.411%), and the reference (87.58 ± 1.352%) site categories. Tukey HSD post hoc

comparisons among the four study sites confirmed that Site B differed significantly from each of the other three sites (all p-values were < 0.001), while Sites A, C, and D did not differ significantly from one another (all $p > 0.35$).

This pattern indicates that the primary difference in spirometric function between sites was centered in the FEV_1/FVC ratio at Site B, rather than in the absolute values of FEV_1 or FVC.

Table 4. Spirometric lung function parameters by site category.

Parameter	Site A	Site B	Site C	Site D	*p*-Value
FEV_1 (L)	1.715 ± 0.335	1.669 ± 0.347	1.736 ± 0.336	1.793 ± 0.322	0.171
FVC (L)	1.965 ± 0.383	1.957 ± 0.403	1.984 ± 0.386	2.048 ± 0.368	0.225
FEV_1/FVC (%)	87.28 ± 1.527	85.33 ± 1.805	87.52 ± 1.411	87.58 ± 1.352	<0.001

3.4. Bivariate Correlations Between Radon Concentration, Anthropometrics, and Lung Function

Crude bivariate correlations revealed no direct association between indoor radon levels and unadjusted absolute lung function metrics, FEV1 (Pearson r = −0.011, $p = 0.801$; Spearman ϱ = 0.001, $p = 0.979$), and FVC (Pearson r = −0.005, $p = 0.902$; Spearman ϱ = 0.004, $p = 0.928$). However, FEV1 and FVC exhibited strong correlations with age (r = 0.869; $p \leq 0.001$ and r = 0.879; $p \leq 0.001$, respectively), height (r = 0.911; $p \leq 0.001$ and r = 0.917; $p \leq 0.001$), and weight (r = 0.854; $p \leq 0.001$ and r = 0.858; $p \leq 0.001$). These findings corroborate the affirmation that growth-related anthropometric factors are the predominant determinants of absolute lung volume in the paediatric population [62–64]. In contrast, the concentration of indoor radon exhibited a modest inverse correlation with FEV_1/FVC. The Pearson correlation coefficient was r = −0.137 ($p = 0.002$), whereas the Spearman correlation coefficient was ϱ = −0.089 ($p = 0.045$). Despite being statistically significant, the strength of these correlations was minimal. Because both radon concentration and FEV_1/FVC differed between study sites, these crude associations were further evaluated using multivariable models in the following subsection.

3.5. Multivariable Regression Analysis

Table 5 presents the results of multivariable linear regression models estimating the association between indoor radon concentration (per 100 Bq/m³ increment) and each spirometric outcome, across three sequential levels of covariate adjustment.

Table 5. Multivariable linear regression: association between indoor radon concentration (per 100 Bq/m³) and spirometric outcomes.

Outcome/Model	B	SE	T	*p*-Value	R^2
FEV_1 (L); Model 1	−0.0016	0.0063	−0.253	0.801	0.0001
FEV_1 (L); Model 2	0.0019	0.0024	0.792	0.429	0.8576
FEV_1 (L); Model 3	0.0019	0.0024	0.823	0.411	0.8599
FVC (L); Model 1	−0.0009	0.0072	−0.124	0.902	0.0000
FVC (L); Model 2	0.0029	0.0026	1.139	0.255	0.8723
FVC (L); Model 3	0.0030	0.0026	1.146	0.252	0.8725
FEV_1/FVC (%); Model 1	−0.1034	0.0330	−3.132	0.0018	0.0189
FEV_1/FVC (%); Model 2	−0.0991	0.0329	−3.016	0.0027	0.0417
FEV_1/FVC (%); Model 3	−0.1028	0.0263	−3.907	<0.001	0.3866

Model 1: unadjusted. Model 2: adjusted for age, height, and weight. Model 3: fully adjusted (Model 2 covariates plus gender). SE: standard error; B: Regression Coefficient. The coefficient shown is for the radon predictor (per 100 Bq/m³) in each model; R^2 is the model's overall explained variance, and t is the t-statistic.

For FEV1, the unadjusted (crude) model showed no significant association with radon concentration (B = −0.0016 L per 100 Bq/m³, t = −0.253, $p = 0.801$). In Model 2 (adjusted for age, height, and weight), the radon coefficient remained small and non-significant (B = 0.0019, t = 0.792, $p = 0.429$), while height (B = 1.833, t = 18.80, $p < 0.001$) and age (B = 0.054, t = 3.69, $p < 0.001$) emerged as significant predictors. In the fully adjusted Model 3 (additionally including gender), radon concentration remained non-significantly associated with FEV1 (B = 0.0019 L per 100 Bq/m³, t = 0.823, $p = 0.411$), as did weight (B = 0.0041, t = 0.994, $p = 0.321$). Height remained the dominant predictor (B = 1.844, t = 19.03, $p < 0.001$), and gender was independently and significantly associated with FEV1 (B = −0.0328, t = −2.920, $p = 0.0037$).

For FVC, a parallel pattern was observed. The crude model showed no association between radon and FVC (B = −0.0009, t = −0.124, $p = 0.902$). In the fully adjusted Model 3, radon concentration remained non-significantly associated with FVC (B = 0.0030 L per 100 Bq/m³, t = 1.146, $p = 0.252$), as did weight (B = −0.0043, t = −0.958, $p = 0.339$) and gender (B = −0.0107, t = −0.867, $p = 0.386$). Height (B = 2.082, t = 19.61, $p < 0.001$) and age (B = 0.091, t = 5.67, $p < 0.001$) remained significant independent predictors.

In contrast, the FEV1/FVC ratio demonstrated a significant, independent inverse correlation with indoor radon concentration, which persisted across all three levels of adjustment. In the unadjusted model, each 100 Bq/m³ increase in radon concentration was associated with a 0.103 percentage-point decrease in FEV1/FVC (B = −0.103, t = −3.132, $p = 0.0018$). This association remained statistically significant in Model 2 (B = −0.099, t = −3.016, $p = 0.0027$) and in the fully adjusted Model 3 (B = −0.103, t = −3.907, $p < 0.001$). In the fully adjusted model, gender emerged as the most influential independent predictor of FEV1/FVC (B = 2.115, t = 16.87, $p < 0.001$). Conversely, age ($p = 0.127$), height ($p = 0.503$), and weight ($p = 0.083$) were not significant predictors after accounting for radon and gender.

3.6. Sensitivity Analysis—Excluding Site B

Because Site B was characterised by both relatively high radon concentrations and the lowest FEV_1/FVC ratio, a sensitivity analysis was performed by excluding Site B to determine whether the observed pooled association was disproportionately influenced by this site. The sensitivity analysis therefore included Sites A, C, and D and retained adjustment for age, height, weight, and gender.

Following exclusion of Site B, radon concentration remained non-significantly associated with lung function, FEV_1 (B = 0.0046 L per 100 Bq/m³, $p = 0.139$). For FVC, a small positive association was observed (B = 0.0068 L per 100 Bq/m³, $p = 0.048$); however, this finding was not accompanied by a corresponding association with FEV_1 and was not observed in the primary analysis.

The association between radon concentration and FEV_1/FVC was essentially null (B ≈ −0.00001 percentage points per 100 Bq/m³, $p = 0.960$). The previously observed between-site difference in FEV_1/FVC was no longer statistically significant in the fully adjusted comparison among Sites A, C, and D (Table 6).

The sensitivity analysis therefore substantially attenuated the apparent radon–FEV_1/FVC association observed in the full cohort and indicates that the pooled relationship was influenced by Site B.

Table 6. Sensitivity Analysis-Excluding Site B.

Outcome/Model	B	*p*-Value	Interpretation
FEV_1 (L)	+0.0046	0.139	No significant association between radon and FEV_1
FVC (L)	+0.0068	0.048	Small positive association with radon; borderline and exploratory
FEV_1/FVC (%)	−0.00001	0.960	No significant association between radon and FEV_1/FVC after exclusion of Site B

4. Discussion

This cross-sectional study assessed indoor radon levels and spirometric lung function among 512 primary school children attending schools situated near active, decommissioned, and prospective mining areas, as well as reference schools located at a distance from mining activities. Three findings are particularly important.

First, indoor radon concentrations differed between study sites, ranging from a mean of 62 Bq/m^3 at the reference site to 257 Bq/m^3 at Site B, with outlier measurements reaching 882 Bq/m^3. This confirms substantial heterogeneity in indoor radon exposure across the participating schools.

Furthermore, the primary distinction in pulmonary function between locations was the FEV_1/FVC ratio, not the absolute values of FEV_1 or FVC. Site B had a lower mean FEV_1/FVC ratio than the other three sites, which showed similar ratios. This site-specific trend is important, as Site B also recorded one of the highest average radon concentrations.

The apparent inverse association between radon and FEV_1/FVC observed in the pooled bivariate analysis was not robust to adjustment for study site. Once site B was excluded in the multivariable models, radon concentration was no longer significantly associated with FEV_1/FVC. These findings indicate that the pooled inverse association should not be interpreted as evidence of an independent or causal effect of radon on the FEV_1/FVC ratio.

The notable characteristic of the dataset was the coexistence of relatively high radon concentrations and a lower FEV_1/FVC ratio at Site B. However, the sensitivity analysis illustrates the reasons why this pattern warrants caution. After the exclusion of Site B, the association between radon and FEV_1/FVC was essentially null. This finding aligns with the limited and heterogeneous body of evidence concerning the non-cancer respiratory effects of radon in children. Notably, a study involving school-aged children reported no significant correlations between radon exposure and spirometric parameters, including FEV_1, FVC, and FEV_1/FVC [65,66].

This indicates that the initial pooled association is likely mainly due to heterogeneity between sites rather than a uniform exposure–response relationship applicable to all schools. It seems that Site B does have some significant source of potential confounding. Radon concentration is not randomly distributed across the sites; therefore, an association observed when aggregating all children may partly be influenced by other characteristics.

Potential site-related factors include building construction and foundation attributes, ventilation systems, classroom occupancy levels, soil and geological profiles, socioeconomic circumstances, proximity to mining infrastructure, indoor particulate matter exposure, environmental tobacco smoke, and other unmeasured environmental or behavioural factors influencing respiratory health, such as particulate matter and mould.

Essentially, the lower FEV_1/FVC ratio observed at Site B should be regarded as an epidemiological indicator; however, it does not constitute definitive evidence that radon caused airway obstruction in these children. The absence of significant associations between radon concentration and FEV_1 or FVC was consistent across the primary models. This is relevant because FEV_1 and FVC are strongly influenced by normal childhood growth. In the present cohort, age, height, and weight showed strong correlations with

absolute lung volumes, and height was a particularly strong predictor in the adjusted models. This pattern is consistent with the established paediatric spirometric reference studies, which demonstrate that age and, particularly, standing height, are primary determinants of FEV_1 and FVC [67–69].

The lack of an association between radon and absolute lung volumes therefore suggests that, within this cross-sectional dataset, there was no detectable relationship between measured indoor radon concentration and the overall size of the expiratory lung volumes. However, the absence of a statistically significant association should not be interpreted as evidence that radon has no respiratory effects in children. Exposure misclassification and limited exposure duration in radon measurement may have reduced the ability to detect small effects.

The initial pooled analysis suggested an inverse association between radon and FEV_1/FVC [70–72], which could superficially be interpreted as a flow-predominant or obstructive pattern. However, the site-adjusted and sensitivity analyses substantially weaken this interpretation.

In particular, the disappearance of the association after the exclusion of Site B indicates that the observed reduction in FEV_1/FVC cannot be confidently attributed to a generalised radon-related effect across the study population [66,73–75]. The present findings, therefore, do not provide sufficient evidence to conclude that indoor radon exposure caused early obstructive airway impairment.

This distinction is important because FEV_1/FVC is a ratio derived from two lung function measures and can vary for reasons unrelated to airway disease. In children, interpretation is also age- and growth-dependent, and clinically meaningful assessment generally requires appropriate reference equations and interpretation using age-, sex-, height-, and population-specific expected values. Consequently, the observed between site differences should be interpreted as epidemiological differences in spirometric measurements rather than as diagnostic evidence of airway obstruction. A biological rationale exists for investigating whether chronic radon exposure could influence respiratory health. Radon progeny emit alpha radiation, and inhaled radon progeny can deposit within the respiratory tract. Ionising radiation can induce oxidative stress, DNA damage, and inflammatory responses in exposed tissues [76,77]. These mechanisms provide a biologically plausible basis for investigating potential respiratory consequences of prolonged exposure.

However, biological plausibility does not establish that the specific association observed in this study was caused by radon. The present study was cross-sectional, exposure was characterised at the school level rather than through individual long-term cumulative exposure, and some confounders were not comprehensively measured. Previous studies have highlighted the need to consider various microenvironments, exposure times, and contextual factors when evaluating environmental exposures and respiratory health in children [31,39,65]. Moreover, the sensitivity analysis at Site B substantially attenuated the apparent association with FEV_1/FVC. Therefore, mechanistic explanations involving airway epithelial injury, inflammation, or remodelling following chronic radon exposure in children should be presented as hypotheses warranting further investigation rather than as mechanisms demonstrated by the current data. Essentially, the cross-sectional design in this study provides a snapshot of exposure and pulmonary function and therefore cannot establish temporal relationships, cumulative exposure effects, or causality. In particular, the present design cannot determine whether differences in spirometric function persist over time or whether prolonged radon exposure is associated with subsequent changes in pulmonary function. Prospective longitudinal studies with repeated school and residential radon measurements and serial spirometric assessments are therefore needed to evaluate respiratory trajectories and potential chronic effects of radon exposure throughout the participants' childhood.

Strengths and Limitations

The strengths of this study include the direct measurement of indoor radon concentrations within classroom environments, rather than dependence on geocoded or modelled exposure estimates, thus delivering school-specific assessments of the actual indoor concentrations. Moreover, lung function was evaluated objectively through spirometry, including FEV_1, FVC, and FEV_1/FVC ratios, which are well-established indicators of expiratory lung function in children [78,79]. The study adhered to the standardised ATS/ERS spirometric methodology and comprehensive adjustment for demographic and anthropometric covariates [50,51,53], with the use of sequential adjustment for age, height, weight, and gender to enable assessment of whether the observed relationships were robust to major determinants of paediatric lung function. We used Site D (location not in direct proximity to metal mining activities, either present, past, or prospective) as a reference/control location to compare with Sites A, B, and C. The study was conducted under formal institutional ethical oversight, with approval obtained from the relevant research ethics committee prior to participant recruitment and data collection, to ensure that participant rights and welfare, risk–benefit considerations, and informed consent were appropriately addressed [80,81]. The internal validity of the study is further strengthened with the exclusion of participants with respiratory pathologies or those with inappropriate spirometric volumes—respiratory illness can alter lung function, while technically unacceptable manoeuvres can produce unreliable FEV_1/FVC measurements [53,82]. The sensitivity analysis showed that the apparent inverse association between radon concentration and FEV_1/FVC was highly sensitive to the inclusion of Site B. After excluding Site B, the association was essentially null. This finding supports the interpretation that the pooled association was influenced by site-level heterogeneity. However, it also limits the ability to determine whether the Site B pattern reflected radon exposure, residual confounding, or other environmental characteristics unique to that location.

The study has limitations: it is cross-sectional, providing a snapshot evaluation and preventing assessment of changes over time or causality [83–85]. Radon exposure was measured at the school level, which may not reflect individual or cumulative exposure, as children spend time outside school, including at home [86]. Residential radon exposure is an important additional source of potential exposure misclassification and confounding. Therefore, classroom measurements cannot be interpreted as the sole indicators of individual cumulative radon exposure. The study also did not evaluate long-term radon exposure, which would be indicative of chronic respiratory effects. Furthermore, it would be helpful to monitor indoor particulate matter along with indoor radon to provide a clearer picture. A 95.7% response rate minimises concerns regarding participation bias; however, it does not entirely eliminate it. While the high rate suggests little non-response bias, the 4.3% of non-participants may differ in respiratory health, exposure, or socioeconomic factors.

5. Conclusions

This study identified differences in classroom radon concentrations across schools, with higher concentrations observed in certain areas near mining sites.

After adjustment for age, height, weight, and gender, the pooled analysis indicated an inverse association between classroom radon concentration and FEV_1/FVC. However, this association was essentially eliminated after excluding Site B. No significant association was observed between radon concentration and either FEV_1 or FVC. Therefore, these findings do not provide sufficient evidence of a consistent or independent relationship between classroom radon exposure and pulmonary function in this cohort.

These findings are hypothesis-generating and underscore the need for panel studies incorporating repeated measurements of radon levels in schools and residences,

assessments of respiratory symptoms, and serial pulmonary function testing to determine whether chronic radon exposure affects respiratory health in South African children.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the University of Johannesburg, Faculty of Health Sciences Research Ethics Committee (REC-2969-2024, 12 August 2024, and subsequent ethics renewals on 10 August 2025 and 4 August 2026).

Informed Consent Statement: Written informed consent was obtained from the parents or legal guardians of all participating children prior to enrolment, and age-appropriate assent was obtained directly from participating children, consistent with international guidance on the ethical conduct of paediatric environmental health research. Permission to conduct the study within school premises was obtained from the relevant provincial Department of Education. Participation was entirely voluntary, and parents and children were informed of their right to withdraw from the study at any stage without consequence. Written informed consent has been obtained from the participants to publish this paper.

Data Availability Statement: The data are available upon reasonable request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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