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Comparative Analysis of the Effect of Natural and Mechanical Ventilation Systems on Indoor Radon Concentration in Offices within a Tertiary Institution in Southwestern Nigeria

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ABSTRACT

Radon is a colourless, odourless, tasteless radioactive gas that build up unnoticed within interior spaces, particularly in poorly ventilated rooms. Radon stands as a notable inAkpofureAdoor air contaminant and the second leading cause of lung cancer after tobacco smoking. The aim of this study was to carry out a comparative analysis of the effect of natural and artificial ventilation systems on indoor radon concentration in offices within LAUTECH Ogbomoso. Indoor radon concentration was measured using the RAD7 Radon Detector for six ventilation conditions comprising three natural ventilation conditions (windows open only, doors open only, and both windows and doors open) and three artificial ventilation conditions (fans only, air conditioners only, and both fans and air conditioners). The Annual Effective Dose Equivalent (AEDE) and Excess Lifetime Cancer Risk (ELCR) were estimated from the measured radon concentrations. For natural ventilation, the combined opening of windows and doors generally produced lower indoor radon concentrations (4.879 – 11.062 Bq m^{-3}) than opening windows only (5.868 – 13.176 Bq m^{-3}) or doors only (7.804 – 19.063 Bq m^{-3}). For artificial ventilation, offices utilizing fans recorded the lowest radon concentrations (5.285 – 7.554 Bq m^{-3}), followed by combined fan-and-air-conditioner use (9.696 – 13.596 Bq m^{-3}), while air-conditioner-only offices recorded the highest concentrations (7.790 – 15.849 Bq m^{-3}). One-way ANOVA confirmed that ventilation condition significantly influenced indoor radon concentration for both natural ventilation ($F = 6.071$, $p = 0.007$) and artificial ventilation ($F = 42.360$, $p = 1.3 \times 10^{-8}$). Nevertheless, all measured indoor radon concentrations, AEDE values, and ELCR values remained below the reference limits recommended by the World Health Organization (WHO), the International Commission on Radiological Protection (ICRP), and the United States Environmental Protection Agency (EPA). The study established that adequate ventilation is an effective means of reducing indoor radon accumulation and improving indoor environmental quality in office buildings. This research contributes to the achievement of Sustainable Development Goal 3 (SDG3) of good health and well-being.

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1. INTRODUCTION

Radon is a naturally occurring radioactive gas produced from the decay of uranium in soil, rocks, and groundwater. Because it is colourless, odourless, and tasteless, it can accumulate indoors without detection, particularly in poorly ventilated buildings, thereby posing significant health risks to occupants (Felicioni *et al.,* 2023). Radon enters buildings mainly through cracks in foundations, gaps in floors and walls, and openings around utility pipes, while its accumulation is influenced by geological conditions, soil permeability, building characteristics, and ventilation rate (Venoso *et al.,* 2021; Abed *et al.,* 2024). Long-term exposure to elevated indoor radon concentrations is recognized as the second leading cause of lung cancer after tobacco smoking, prompting the World Health Organization (WHO) and the United States Environmental Protection Agency (EPA) to establish reference levels for indoor radon concentration to protect public health (WHO, 2023; EPA, 2023).

Ventilation remains one of the most effective and practical methods for reducing indoor radon concentration by increasing air exchange and removing radon-laden air. Natural ventilation and artificial (mechanical) ventilation are the two major approaches used to improve indoor air quality; however, their effectiveness depends on factors such as building design, operational efficiency, climatic conditions, and air exchange rate (Bulut and Şahin, 2024). Consequently, selecting an appropriate ventilation strategy is essential for minimizing radon accumulation and reducing the associated radiological health risks.

The studies investigated indoor radon concentrations in different buildings and evaluated the effectiveness of ventilation systems. However, the reported findings remain inconsistent because of differences in building characteristics, environmental conditions, ventilation practices, and geographical settings (Park *et al.,* 2020; Abed *et al.,* 2024). In Nigeria, several studies have focused on measuring indoor radon concentration and estimating radiation doses in residential, institutional, and workplace environments (Usikalu *et al.,* 2020; Bashir *et al.,* 2023; Oni *et al.,* 2025a). Comparatively, fewer studies have evaluated the relative performance of natural and artificial ventilation systems in reducing indoor radon concentration in office buildings, particularly within tropical environments (Kumar *et al.,* 2026).

This study also estimates the Annual Effective Dose Equivalent (AEDE) and Excess Lifetime Cancer Risk (ELCR) associated with radon exposure and evaluates the influence of different ventilation conditions using one-way Analysis of Variance (ANOVA). The findings provide evidence that can support effective indoor radon management, improve indoor environmental quality, and contribute to the protection of occupants' health in office buildings. the aim comparative effects of natural and artificial ventilation systems on indoor radon concentration in selected offices within Ladoke Akintola University of Technology (LAUTECH), Ogbomoso.

2. MATERIALS AND METHODS

Study Area

This study was carried out within the premises of Ladoke Akintola University of

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Technology (LAUTECH), located in Ogbomoso, Oyo State, Nigeria. LAUTECH is a prominent public university known for its emphasis on science, engineering, and technology, and it occupies a substantial landmass situated along the Ogbomoso-Ilorin Road. Geographically, the university lies between latitude 8°08'N and longitude 4°15'E, positioned within the transitional ecological zone between the tropical rainforest and savannah belt of southwestern Nigeria. The climate is typically tropical, with distinct wet and dry seasons. The average annual temperature ranges from 24°C to 32°C, and relative humidity often varies between 55% and 80%, factors which are known to influence both indoor air quality and the effectiveness of natural ventilation.

LAUTECH comprises a variety of academic, administrative, and research buildings, many of which differ in architectural design, orientation, building materials, occupancy patterns, and ventilation systems. Natural ventilation in these buildings typically occurs through windows, doors, louvres, and vents, while artificial ventilation systems include mechanical fans, and split air conditioning systems.

Sampling Points

The sampling points for this study comprised selected offices within LAUTECH, categorized according to their predominant ventilation systems. To ensure uniformity and minimize the influence of confounding factors on indoor radon concentration, offices with similar structural characteristics were selected, including building dimensions, age, wall materials, ceiling types, and floor finishes. For the natural ventilation category, three ventilation conditions were considered: offices with open windows only, offices with open doors only, and offices with both windows and doors open, with ten radon measurements obtained for each condition (30 readings total). Similarly, for the artificial ventilation category, three conditions were investigated: offices utilizing fans only, offices utilizing air conditioners only, and offices utilizing both fans and air conditioners, again with ten radon measurements per condition (30 readings total).

Measurement of Indoor Radon Concentration

Indoor radon concentration was measured using the RAD7 Radon Detector (Durridge Company Inc., USA), a portable, real-time electronic radon monitor that employs solid-state alpha spectrometry for the detection of radon gas and its short-lived decay products. Measurements were conducted in selected ground-floor offices to minimize variations in radon entry associated with building height. The selected offices had similar structural characteristics and ventilation configurations, each comprising two windows positioned opposite each other, one ceiling fan, and one air-conditioning unit. The RAD7 detector was positioned at a representative breathing-zone height of approximately 1.0–1.5 m above the floor, at least 1–2 m away from walls, windows, doors, and direct ventilation outlets. Before each measurement, relevant information about the sampling location was documented, including the office identification code, floor level, ventilation condition, occupancy status, date and time of sampling, ambient

temperature, and relative humidity. The indoor radon concentration for each office was calculated as the arithmetic mean of the stable cycle readings obtained during the measurement period, and duplicate measurements were conducted in selected offices to verify consistency and reproducibility.

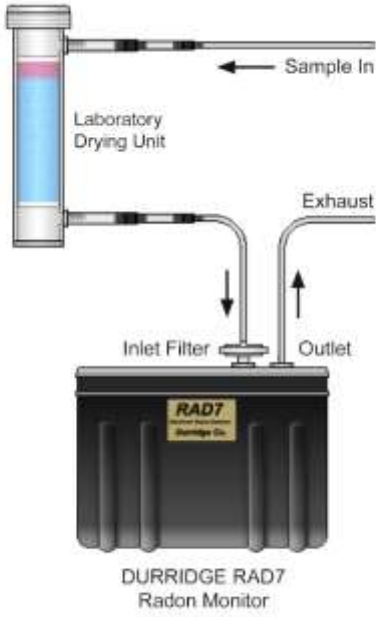


Figure 1: Diagram of RAD7 Radon Detector

Estimation of Annual Effective Dose Equivalent

The annual effective dose equivalent from radon inhalation was estimated using the equation recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR):

$$AEDE = C \times F \times O \times T \times D \quad (1)$$

Where: C = average indoor radon concentration (Bq/m³); F = equilibrium factor between radon and its progeny (typically 0.4 for indoor environments); O = occupancy factor (fraction of time spent indoors); T = indoor occupancy time (hours per year); D = dose conversion factor (9×10^{-6} mSv per Bq·h/m³) (Aliyu *et al.*, 2021).

Estimation of Excess Lifetime Cancer Risk

The Excess Lifetime Cancer Risk (ELCR) was estimated using the formula recommended by the United States Environmental Protection Agency (EPA, 2019) and the International Commission on Radiological Protection (ICRP):

$$ELCR = C \times F \times T \times DL \times RF \quad (2)$$

Where: C = average indoor radon concentration; F = equilibrium factor for

radon indoors; T = exposure time; DL = average duration of life; RF = risk factor for developing lung cancer per unit radon exposure (Azhdarpoor *et al.,* 2021).

Statistical Analysis

Data collected in this study were subjected to comparative, correlative, and regression-based statistical analyses to evaluate the influence of ventilation systems on indoor radon concentration. Descriptive statistics (mean, standard deviation, minimum, and maximum) were computed for each ventilation condition, and a one-way ANOVA was employed to determine whether statistically significant differences existed between the natural and artificial ventilation categories at a 95% confidence level ($p < 0.05$).

3. RESULTS AND DISCUSSION

Indoor Radon Concentration

Tables 1–3 show the natural ventilation for indoor radon concentration, Annual Effective Dose Equivalent (AEDE) and Excess Lifetime Cancer Risk (ELCR) for offices with open windows only, open doors only, and both windows and doors open, respectively.

Table 1: Indoor Radon Concentration, Annual Effective Dose Equivalent **(**AEDE) and Excess Lifetime Cancer Risk (ELCR) for offices with open windows only

Office	Indoor Radon Concentration (Bq m^{-3})	Annual Effective Dose Equivalent (mSv y^{-1})	Excess Lifetime Cancer Risk
1	10.952 ± 4.138	0.276	9.66×10^{-4}
2	11.846 ± 4.087	0.298	1.04×10^{-3}
3	7.619 ± 1.419	0.192	6.72×10^{-4}
4	5.868 ± 1.949	0.148	5.18×10^{-4}
5	6.846 ± 2.083	0.173	6.04×10^{-4}
6	11.953 ± 3.641	0.301	1.05×10^{-3}
7	7.790 ± 2.553	0.196	6.87×10^{-4}
8	6.356 ± 1.344	0.160	5.60×10^{-4}
9	9.292 ± 3.307	0.234	8.19×10^{-4}
10	13.176 ± 3.752	0.332	1.16×10^{-3}

Table 2: Indoor Radon Concentration, Annual Effective Dose Equivalent **(**AEDE) and Excess Lifetime Cancer Risk (ELCR)for offices with open door only

Office	Indoor Radon Concentration (Bq m^{-3})	Annual Effective Dose Equivalent (mSv y^{-1})	Excess Lifetime Cancer Risk
1	10.645 ± 0.644	0.268	9.39×10^{-4}
2	7.804 ± 1.224	0.197	6.88×10^{-4}
3	9.373 ± 0.669	0.236	8.26×10^{-4}
4	16.535 ± 4.602	0.417	1.46×10^{-3}

Office	Indoor Radon Concentration (Bq m^{-3})	Annual Effective Dose Equivalent (mSv y^{-1})	Excess Lifetime Cancer Risk
5	16.835 ± 5.452	0.424	1.48×10^{-3}
6	10.470 ± 2.063	0.264	9.23×10^{-4}
7	10.974 ± 1.815	0.277	9.68×10^{-4}
8	15.535 ± 5.102	0.391	1.37×10^{-3}
9	19.063 ± 5.361	0.480	1.68×10^{-3}
10	13.452 ± 2.888	0.339	1.19×10^{-3}

Table 3: Indoor Radon Concentration, Annual Effective Dose Equivalent **(**AEDE) and Excess Lifetime Cancer Risk (ELCR) for offices with both windows and doors open

Office	Indoor Radon Concentration (Bq m^{-3})	Annual Effective Dose Equivalent (mSv y^{-1})	Excess Lifetime Cancer Risk
1	6.567 ± 3.166	0.165	5.79×10^{-4}
2	7.779 ± 3.412	0.196	6.86×10^{-4}
3	11.062 ± 5.131	0.279	9.76×10^{-4}
4	4.879 ± 1.890	0.123	4.30×10^{-4}
5	10.779 ± 5.272	0.272	9.51×10^{-4}
6	10.706 ± 5.347	0.270	9.45×10^{-4}
7	8.347 ± 3.128	0.210	7.37×10^{-4}
8	7.440 ± 2.730	0.187	6.57×10^{-4}
9	10.711 ± 5.306	0.270	9.45×10^{-4}
10	10.737 ± 5.312	0.271	9.47×10^{-4}

Tables 4–6 show the artificial ventilation for Indoor Radon Concentration, Annual Effective Dose Equivalent (AEDE) and Excess Lifetime Cancer Risk (ELCR) for offices utilizing fans only, air conditioners only, and both fans and air conditioners, respectively.

Table 4: Indoor Radon Concentration, Annual Effective Dose Equivalent **(**AEDE) and Excess Lifetime Cancer Risk (ELCR) for offices utilizing fans only

Office	Indoor Radon Concentration (Bq m^{-3})	Annual Effective Dose Equivalent (mSv y^{-1})	Excess Lifetime Cancer Risk
1	5.285 ± 1.973	0.133	4.67×10^{-4}
2	7.311 ± 2.318	0.184	6.45×10^{-4}
3	6.887 ± 1.436	0.174	6.08×10^{-4}
4	6.670 ± 1.728	0.168	5.89×10^{-4}
5	6.914 ± 1.964	0.174	6.10×10^{-4}
6	7.381 ± 1.912	0.186	6.52×10^{-4}

Office	Indoor Radon Concentration (Bq m^{-3})	Annual Effective Dose Equivalent (mSv y^{-1})	Excess Lifetime Cancer Risk
7	5.881 ± 1.992	0.148	5.19×10^{-4}
8	6.503 ± 2.030	0.164	5.74×10^{-4}
9	7.554 ± 1.886	0.191	6.67×10^{-4}
10	5.832 ± 2.083	0.147	5.15×10^{-4}

Table 5: Indoor Radon Concentration, Annual Effective Dose Equivalent **(**AEDE) and Excess Lifetime Cancer Risk (ELCR) for offices utilizing air conditioners only

Office	Indoor Radon Concentration (Bq m^{-3})	Annual Effective Dose Equivalent (mSv y^{-1})	Excess Lifetime Cancer Risk
1	15.849 ± 4.957	0.400	1.40×10^{-3}
2	8.297 ± 0.973	0.209	7.33×10^{-4}
3	9.641 ± 1.448	0.243	8.52×10^{-4}
4	9.821 ± 1.064	0.248	8.68×10^{-4}
5	7.790 ± 1.222	0.197	6.88×10^{-4}
6	11.299 ± 1.473	0.285	9.98×10^{-4}
7	10.474 ± 1.565	0.264	9.25×10^{-4}
8	11.670 ± 1.463	0.294	1.03×10^{-3}
9	8.792 ± 0.722	0.222	7.76×10^{-4}
10	8.560 ± 1.272	0.216	7.56×10^{-4}

Table 6: Indoor Radon Concentration for offices utilizing fans and air conditioners

Office	Indoor Radon Concentration (Bq m^{-3})	Annual Effective Dose Equivalent (mSv y^{-1})	Excess Lifetime Cancer Risk
1	11.322 ± 1.303	0.286	1.00×10^{-3}
2	10.677 ± 0.430	0.269	9.43×10^{-4}
3	10.983 ± 0.979	0.277	9.70×10^{-4}
4	9.696 ± 0.718	0.245	8.57×10^{-4}
5	13.021 ± 1.504	0.329	1.15×10^{-3}
6	13.596 ± 1.843	0.343	1.20×10^{-3}
7	10.722 ± 0.603	0.271	9.48×10^{-4}
8	13.478 ± 2.480	0.340	1.19×10^{-3}
9	12.966 ± 1.528	0.327	1.15×10^{-3}
10	12.528 ± 2.287	0.316	1.11×10^{-3}

DISCUSSION *Indoor Radon Concentration*

For natural ventilation, indoor radon concentrations varied according to the ventilation mode employed. The open window condition recorded indoor radon concentrations ranging from (5.868 ± 1.949 to 13.176 ± 3.752 Bq m^{-3}), while the corresponding the Annual Effective Dose Equivalent (AEDE) from (0.148–0.332 mSv y^{-1}) and Excess Lifetime Cancer Risk (ELCR) from (5.18×10^{-4}–1.16×10^{-3}), respectively. These variations may be attributed to differences in building characteristics, air exchange rates, office occupancy, and the efficiency of natural airflow. The relatively low radon concentrations observed for this condition demonstrate that opening windows enhances the dilution and removal of radon through increased outdoor air exchange. Similarly, the resulting AEDE and ELCR values closely followed the trend in radon concentration, confirming the direct relationship between radon exposure, radiation dose, and lifetime cancer risk. Despite the observed variations, all measured values remained below the reference limits recommended by the WHO and ICRP, indicating minimal radiological health risk to occupants. The open-door condition produced relatively higher indoor radon concentrations (7.804 ± 1.224–19.063 ± 5.361 Bq m^{-3}) than the open-window condition. Consequently, AEDE (0.197–0.480 mSv y^{-1}) and ELCR (6.88×10^{-4}–1.68×10^{-3}) were also comparatively higher. Although opening doors facilitates air movement, its effectiveness depends largely on room orientation, prevailing wind direction, surrounding structures, and indoor airflow patterns. Consequently, some offices experienced greater radon accumulation than others, suggesting that open doors alone do not consistently provide sufficient ventilation for efficient radon removal. The open of both windows and doors resulted in the lowest indoor radon concentrations among the natural ventilation strategies, ranging from (4.879 ± 1.890 to 11.062 ± 5.131 Bq m^{-3}), with corresponding AEDE and ELCR values of (0.123–0.279 mSv y^{-1}) and (4.30×10^{-4}–9.76×10^{-4}), respectively. This finding indicates that cross-ventilation substantially improves indoor air exchange, thereby limiting radon accumulation more effectively than either windows or doors alone. The consistently low radiological indices further demonstrate that enhanced natural ventilation is an effective and sustainable approach for reducing indoor radon exposure in office environments.

Indoor radon concentrations for artificial ventilation differed according to the ventilation system employed. Fan-only ventilation produced the lowest radon concentrations (5.285 ± 1.973–7.554 ± 1.886 Bq m^{-3}), with Annual Effective Dose Equivalent (AEDE) ranging from (0.133–0.191 mSv y^{-1}) and Excess Lifetime Cancer Risk (ELCR) from (4.67×10^{-4}–6.67×10^{-4}). The low values indicate that continuous air circulation generated by fans effectively reduced radon accumulation by promoting air movement within the offices, resulting in minimal radiation doses and lifetime cancer risks. The air-conditioner-only condition recorded comparatively higher indoor radon concentrations (7.790 ± 1.222–15.849 ± 4.957 Bq m^{-3}), with AEDE values of (0.197–0.400 mSv y^{-1}) and ELCR values of (6.88×10^{-4}–1.40×10^{-3}). This increase is likely associated with reduced outdoor air exchange

because air conditioners are commonly operated with doors and windows closed while primarily recirculating indoor air. Consequently, radon entering from the for lying soil and building materials tends to accumulate within enclosed spaces. When fans and air conditioners were operated simultaneously, indoor radon concentrations ranged from (9.696 ± 0.718 to 13.596 ± 1.843 Bq m^{-3}), while AEDE and ELCR ranged from (0.245–0.343 mSv y^{-1}) and (8.57 × 10^{-4}–1.20 × 10^{-3}), respectively. Although the fan improved indoor air circulation, the simultaneous use of air conditioning for closed-building conditions appeared to restrict fresh air exchange, resulting in radon concentrations that were generally higher than those observed for fan-only ventilation. Nevertheless, all measured radon concentrations, AEDE, and ELCR values remained below internationally recommended safety limits, indicating that none of the investigated artificial ventilation conditions posed significant radiological health risks. Overall, fan-only ventilation was the most effective artificial ventilation strategy for minimizing indoor radon concentration, whereas air-conditioner-only operation was the least effective due to limited ventilation with outdoor air.

One-Way Analysis of Variance (ANOVA)

A one-way ANOVA was performed at a 95% confidence level ($\alpha = 0.05$) to determine whether statistically significant differences existed in mean indoor radon concentration among the ventilation conditions investigated. The descriptive statistics showed average indoor radon concentrations of 8.97, 13.34, and 9.16 Bq m^{-3} for the window-open-only, door-open-only, and both-open conditions respectively, with variances of 7.39, 15.03, and 4.67. The calculated F-value (6.071) exceeded the critical F-value (3.403), and the associated p-value (0.007) was less than 0.05; the null hypothesis was therefore rejected, indicating that the type of natural ventilation employed has a statistically significant influence on indoor radon concentration.

The mean indoor radon concentrations were 6.77, 9.59, and 11.96 Bq m^{-3} for the fan-only, air-conditioner-only, and combined fan-and-air-conditioner conditions respectively. The calculated F-value (42.360) was considerably greater than the critical F-value (3.403), while the associated p-value (1.3×10^{-8}) was far below 0.05; the null hypothesis was therefore rejected, indicating that the type of artificial ventilation employed significantly influences indoor radon concentration. Based on the group means, fan-only ventilation recorded the lowest mean indoor radon concentration, followed by air-conditioner-only, while the combined use of fan and air conditioner recorded the highest mean concentration.

Annual Effective Dose Equivalent (AEDE)

The Annual Effective Dose Equivalent (AEDE) for the natural ventilation conditions is presented. The open-window-only condition recorded AEDE values ranging from (0.148 to 0.332 mSv y^{-1}), whereas the open-door-only condition produced comparatively higher values of (0.197–0.480 mSv y^{-1}). In contrast, the combined open-window and open-door condition yielded the lowest AEDE values (0.123–0.279 mSv y^{-1}). The variation in AEDE closely reflected the

corresponding indoor radon concentrations, demonstrating the direct relationship between radon exposure and the annual radiation dose received by occupants. The lower AEDE observed for the combined window-and-door condition indicates that enhanced cross-ventilation improves indoor–outdoor air exchange, thereby promoting the dilution and removal of radon before it accumulates indoors. Conversely, relying solely on open doors resulted in relatively higher radiation doses, suggesting less effective radon removal due to limited air circulation. Although differences were observed among the natural ventilation strategies, all estimated AEDE values remained below the 1 mSv y^{-1} annual public dose limit recommended by the International Commission on Radiological Protection (ICRP), indicating that radiation exposure to office occupants was low. These findings suggest that improving natural ventilation, particularly through effective cross-ventilation, is a practical and cost-effective approach for reducing indoor radon exposure and the associated radiation dose.

The AEDE values for the artificial ventilation conditions are presented. For the fan-only condition, AEDE ranged from (0.133 to 0.191 mSv y^{-1}), representing the lowest radiation doses among the artificial ventilation strategies. Air-conditioner-only operation recorded comparatively higher AEDE values (0.197–0.400 mSv y^{-1}), while the combined fan and air-conditioner condition produced intermediate values ranging from (0.245 to 0.343 mSv y^{-1}). These variations closely followed the corresponding indoor radon concentrations, confirming that increased radon accumulation results in higher annual radiation doses. The relatively low AEDE associated with fan-only ventilation suggests that continuous air circulation enhances radon dilution and removal. In contrast, air conditioners, which primarily recirculate indoor air and are commonly operated with doors and windows closed, reduce fresh air exchange and promote radon accumulation, thereby increasing radiation exposure. The combined use of fans and air conditioners improved indoor air movement but did not provide sufficient fresh air exchange to achieve the low AEDE values observed for fan-only ventilation. Nevertheless, all estimated AEDE values remained well below the ICRP recommended annual public dose limit of 1 mSv y^{-1}, indicating that occupants of the investigated offices were exposed to relatively low radiation doses irrespective of the artificial ventilation method. Overall, fan-only ventilation proved to be the most effective artificial ventilation strategy for minimizing annual radiation dose, whereas air-conditioner-only operation resulted in the highest occupant exposure due to reduced ventilation with outdoor air.

Excess Lifetime Cancer Risk (ELCR)

The Excess Lifetime Cancer Risk (ELCR) estimated for the natural ventilation conditions is presented. The open-window-only condition produced ELCR values ranging from 5.18×10^{-4} to 1.16×10^{-3}, while the open-door-only condition recorded comparatively higher values of 6.88×10^{-4} to 1.68×10^{-3}. In contrast, the combined open-window and open-door condition yielded the lowest ELCR values, ranging from 4.30×10^{-4} to 9.76×10^{-4}. The observed variation

closely mirrored the corresponding indoor radon concentrations and Annual Effective Dose Equivalent (AEDE), demonstrating that increased radon exposure results in higher radiation doses and a greater estimated lifetime risk of radon-induced lung cancer. Among the natural ventilation strategies, simultaneous opening of windows and doors was the most effective in reducing ELCR, highlighting the importance of cross-ventilation in limiting indoor radon accumulation. Conversely, reliance on open doors alone resulted in comparatively higher ELCR values, indicating less efficient radon removal. Although the three ventilation conditions differed in their effectiveness, all estimated ELCR values remained relatively low, reflecting the low indoor radon concentrations measured throughout the study. These findings suggest that effective natural ventilation, particularly through cross-ventilation, is a simple, sustainable, and cost-effective strategy for minimizing the long-term radiological health risks associated with indoor radon exposure in office environments.

The ELCR values estimated for the artificial ventilation conditions are presented. Fan-only ventilation produced the lowest ELCR values (4.67×10^{-4}–6.67×10^{-4}), whereas air-conditioner-only operation resulted in the highest estimated lifetime cancer risk (6.88×10^{-4}–1.40×10^{-3}). The combined fan and air-conditioner condition produced intermediate ELCR values ranging from (8.57×10^{-4} to 1.20×10^{-3}). These variations followed the same trend observed for indoor radon concentration and AEDE, confirming the strong relationship between radon exposure, radiation dose, and the estimated probability of developing lung cancer over a lifetime. The lower ELCR associated with fan-only ventilation indicates that improved air circulation effectively limits radon accumulation, whereas the relatively higher values observed for air-conditioner-only and combined ventilation conditions are likely due to reduced fresh air exchange when doors and windows remain closed. Nevertheless, all estimated ELCR values were relatively low, indicating that the measured indoor radon concentrations do not pose a significant lifetime radiological health risk to office occupants. Overall, the findings demonstrate that artificial ventilation influences long-term radon-related health risk, with fan-only ventilation providing the greatest reduction in excess lifetime cancer risk among the artificial ventilation strategies evaluated.

Comparative Analysis of Natural and Artificial Ventilation Conditions

A comparative assessment of the natural and artificial ventilation strategies demonstrated that the mode of ventilation significantly influenced indoor radon concentration, the Annual Effective Dose Equivalent (AEDE), and the Excess Lifetime Cancer Risk (ELCR). Among the natural ventilation conditions, the simultaneous opening of windows and doors consistently produced the lowest indoor radon concentrations (4.879 ± 1.890–11.062 ± 5.131 Bq m^{-3}), followed by the open-window-only condition (5.868 ± 1.949–13.176 ± 3.752 Bq m^{-3}), whereas the open-door-only condition recorded the

highest concentrations (7.804 ± 1.224–19.063 ± 5.361 Bq m^{-3}). The superior performance of the combined window-and-door condition is attributed to enhanced cross-ventilation, which increases indoor–outdoor air exchange and facilitates the dilution and removal of radon before it accumulates within occupied spaces. These findings indicate that cross-ventilation is the most effective natural ventilation strategy for mitigating indoor radon exposure in office environments.

The differences were observed among the artificial ventilation conditions. Fan-only ventilation recorded the lowest indoor radon concentrations (5.285 ± 1.973–7.554 ± 1.886 Bq m^{-3}), demonstrating its effectiveness in promoting air circulation and reducing radon accumulation. The air-conditioner-only operation produced the highest radon concentrations (7.790 ± 1.222–15.849 ± 4.957 Bq m^{-3}), while the combined fan and air-conditioner condition resulted in intermediate concentrations (9.696 ± 0.718–13.596 ± 1.843 Bq m^{-3}). The higher radon levels observed for air-conditioned environments are likely due to reduced fresh air exchange associated with closed windows and doors, which allows radon entering from the soil and building materials to accumulate indoors. The fan improved indoor air movement; it did not fully compensate for the limited outdoor air exchange during simultaneous air-conditioner operation.

The differences in indoor radon concentration were reflected in the corresponding radiological risk indices. Natural ventilation produced AEDE values ranging from (0.123 to 0.480 mSv y^{-1}) and ELCR values of (4.30×10^{-4} to 1.68×10^{-3}), whereas for artificial ventilation, fan-only operation resulted in the lowest AEDE (0.133–0.191 mSv y^{-1}) and ELCR (4.67×10^{-4}–6.67×10^{-4}) values. Air-conditioner-only ventilation recorded comparatively higher AEDE (0.197–0.400 mSv y^{-1}) and ELCR (6.88×10^{-4}–1.40×10^{-3}), while the combined fan and air-conditioner condition produced intermediate values. These results confirm the strong positive relationship between indoor radon concentration, radiation dose, and the estimated lifetime risk of radon-induced lung cancer, emphasizing that ventilation strategies promoting greater fresh air exchange provide more effective protection against radon exposure.

The comparative analysis demonstrates that ventilation systems capable of maximizing indoor–outdoor air exchange are more effective in controlling indoor radon accumulation and minimizing associated radiological health risks. Among the natural ventilation strategies, cross-ventilation achieved by simultaneously opening windows and doors proved to be the most effective, whereas fan-only ventilation performed best among the artificial ventilation methods. Although all measured indoor radon concentrations, AEDE, and ELCR values remained below the guideline limits recommended by the WHO and ICRP, the findings highlight the importance of selecting appropriate ventilation strategies for maintaining good indoor air quality and reducing long-term radon exposure in office buildings. These results provide evidence to support the adoption of effective ventilation practices as a practical and sustainable

approach to radon mitigation in occupational environments.

The permissible limit for Excess Lifetime Cancer Risk (ELCR) from radon exposure is set by international radiation protection bodies. According to the International Commission on Radiological Protection (ICRP), the recommended reference level for indoor radon concentration is between 100 and 300 Bq/m³, with the upper bound of 300 Bq/m³ corresponding to an ELCR of about 0.003 (three chances in a thousand). This is the level used for comparison in homes and workplaces. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) provides a similar benchmark, placing the maximum permissible ELCR at approximately 0.003875. The World Health Organization (WHO) is stricter, recommending a reference level of 100 Bq/m³, which keeps ELCR closer to 0.001**.**

The overview, when comparing your measured ELCR values, the accepted permissible limit is around 0.003 (ICRP), with 0.003875 (UNSCEAR) as the global upper bound, and 0.001 (WHO) as the health-focused target.

4. CONCLUSION

This study carried out a comparative analysis of the effect of natural and artificial ventilation systems on indoor radon concentration in selected offices within LAUTECH, Ogbomoso, using the RAD7 radon detector. All measured radon concentrations, AEDE, and ELCR values remained below WHO, ICRP, and US EPA reference limits, indicating a low radiological health risk to occupants for the conditions studied. The results demonstrate that ventilation strategy is a practical, low-cost lever for indoor radon mitigation in institutional office buildings.

A comparative evaluation of three natural ventilation strategies showed that ventilation strongly influenced indoor radon levels and health risks. Opening both windows and doors simultaneously was the most effective, yielding the lowest radon concentrations (4.879–11.062 Bq/m³), AEDE (0.123–0.279 mSv/y), and ELCR (4.30×10^{-4}–9.76×10^{-4}) due to enhanced cross-ventilation. Window-only ventilation provided moderate reduction, with radon values of 5.868–13.176 Bq/m³, AEDE of 0.148–0.332 mSv/y, and ELCR of 5.18×10^{-4}–1.16×10^{-3}. Door-only ventilation was least effective, recording the highest radon (7.804–19.063 Bq/m³), AEDE (0.197–0.480 mSv/y), and ELCR (6.88×10^{-4}–1.68×10^{-3}) due to poor air circulation. All values remained well below the WHO/ICRP reference level of 300 Bq/m³, confirming minimal radiological risk. Overall, cross-ventilation via windows and doors is the most effective natural strategy for reducing radon exposure in office buildings.

A comparative analysis of artificial ventilation strategies showed that system type significantly affected indoor radon levels and health risks. Fan-only ventilation was most effective, producing the lowest radon concentrations (5.285–7.554 Bq/m³), AEDE (0.133–0.191 mSv/y), and ELCR (4.67×10^{-4}–6.67×10^{-4}), due to improved air circulation and dilution of radon gas. Air-conditioner-only use resulted in higher radon levels (7.790–15.849 Bq/m³), AEDE (0.197–0.400 mSv/y), and ELCR (6.88×10^{-4}–1.40×10^{-3}), attributed to reduced fresh air exchange and recirculation of indoor air.

The combined fan-and-air-conditioner condition showed intermediate performance, with radon concentrations of 9.696–13.596 Bq/m³, AEDE (0.245–0.343 mSv/y), and ELCR (8.57×10^{-4}–1.20×10^{-3}), but was less effective than fans alone because air conditioners limited outdoor air intake. All measured values remained well below the WHO/ICRP reference level of 300 Bq/m³, confirming low radiological risk. Overall, fan-only ventilation is the most effective artificial strategy for reducing radon exposure, followed by the combined system, while air conditioners alone yield the highest risk indices.

The findings imply that the effectiveness of natural ventilation in reducing radon depends on the degree of air exchange. Opening both windows and doors simultaneously creates cross-ventilation, which enhances airflow, dilutes radon gas, and lowers radiation exposure risks. In contrast, opening only the door provides limited circulation, allowing radon to accumulate at higher levels. Although all measured radon concentrations, AEDE, and ELCR values were well below the WHO and ICRP reference limit of 300 Bq/m³—indicating no immediate radiological concern—the results confirm that cross-ventilation is the most effective, practical, and cost-efficient natural mitigation strategy for maintaining good indoor air quality in office buildings.

The findings indicate that the effectiveness of artificial ventilation in reducing indoor radon depends on whether the system promotes fresh air exchange or simply recirculates indoor air. Fan-only ventilation proved most effective, as it enhanced air movement, diluted radon, and minimized radiation exposure risks. In contrast, air conditioners used alone tended to recirculate indoor air with limited outdoor exchange, leading to higher radon accumulation and elevated AEDE and ELCR values. Combining fans with air conditioners improved circulation compared to air conditioners alone, but remained less effective than fans alone because the air conditioner restricted natural air exchange. Importantly, all measured radon concentrations were well below the WHO and ICRP reference level of 300 Bq/m³, confirming no immediate radiological concern. These results suggest that improving ventilation systems to maximize fresh air exchange, or supplementing air-conditioned spaces with adequate mechanical or natural ventilation, can further reduce radon accumulation and enhance indoor environmental quality in office buildings.

This research contributes to the achievement of Sustainable Development Goal 3 (SDG3) of good health and well-being.

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APPENDIX

Table 7: One-way ANOVA for natural ventilation condition

SUMMARY

Groups	Count	Sum	Average	Variance		
Windows open only	9	80.746	8.971778	7.393517		
Doors open only	9	120.041	13.33789	15.02819		
Both windows and doors open	9	82.44	9.16	4.671863		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	109.6593	2	54.82966	6.071144	0.007351	3.402826
Within Groups	216.7486	24	9.031191			
Total	326.4079	26				

Table 8: One-way ANOVA for artificial ventilation condition

SUMMARY

Groups	Count	Sum	Average	Variance		
Fan only	9	60.933	6.7703333	0.383317		
Air conditioner only	9	86.344	9.5937778	1.8367404		
Fan and air conditioner	9	107.667	11.963	2.0875098		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	121.6465187	2	60.823259	42.360286	1.3E-08	3.402826
Within Groups	34.46053756	24	1.4358557			
Total	156.1070563	26				