sustainability

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Radon in Indoor Air: Towards Continuous Monitoring

Juliana P. Sá [1,2], Pedro T. B. S. Branco [1,2], Maria C. M. Alvim-Ferraz [1,2], Fernando G. Martins [1,2] and Sofia I. V. Sousa [1,2,*]

[1] LEPABE—Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal; julianasa@fe.up.pt (J.P.S.); p.branco@fe.up.pt (P.T.B.S.B.); aferraz@fe.up.pt (M.C.M.A.-F.); fgm@fe.up.pt (F.G.M.)
[2] ALiCE—Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
* Correspondence: sofia.sousa@fe.up.pt; Tel.: +351-22-508-2262

Abstract: Radon poses significant health risks. Thus, the continuous monitoring of radon concentrations in buildings' indoor air is relevant, particularly in schools. Low-cost sensors devices are emerging as promising technologies, although their reliability is still unknown. Therefore, this is the first study aiming to evaluate the performance of low-cost sensors devices for short-term continuous radon monitoring in the indoor air of nursery and primary school buildings. Five classrooms of different age groups (infants, pre-schoolers and primary school children) were selected from one nursery and one primary school in Porto (Portugal). Radon indoor concentrations were continuously monitored using one reference instrument (Radim 5B) and three commercially available low-cost sensors devices (Airthings Wave and RandonEye: RD200 and RD200P2) for short-term sampling (2–4 consecutive days) in each studied classroom. Radon concentrations were in accordance with the typical profiles found in other studies (higher on weekends and non-occupancy periods than on occupancy). Both RadonEye low-cost sensors devices presented similar profiles with Radim 5B and good performance indices (R^2 reaching 0.961), while the Airthings Wave behavior was quite different. These results seem to indicate that the RadonEye low-cost sensors devices studied can be used in short-term radon monitoring, being promising tools for actively reducing indoor radon concentrations.

Keywords: radon; low-cost sensor; continuous monitoring; short-term; schools; children

Citation: Sá, J.P.; Branco, P.T.B.S.; Alvim-Ferraz, M.C.M.; Martins, F.G.; Sousa, S.I.V. Radon in Indoor Air: Towards Continuous Monitoring. *Sustainability* **2022**, *14*, 1529. https://doi.org/10.3390/su14031529

Academic Editor: Elena Cristina Rada

Received: 17 December 2021
Accepted: 26 January 2022
Published: 28 January 2022

1. Introduction

Radon is a naturally occurring radioactive natural gas that results from the decay of uranium in soil, rocks and building-based materials [1]. It is a colorless, odorless and tasteless gas that travels through the soil and enters buildings through foundation fissures [2,3].

In indoor environments, such as homes, schools and office buildings, radon reaches epidemiologically significant levels, which do not occur outdoors [4,5]. In poorly ventilated areas, indoor radon can accumulate at levels up to two orders of magnitude higher than outdoors [6], and concentrations can range from 10 Bq/m^3 to 10,000 Bq/m^3 [2]. Moreover, the World Health Organization (WHO) recognized that radon is one of the most significant environmental threats to public health, being the second leading cause of lung cancer worldwide and the primary one among non-smokers [7]. The importance of monitoring and controlling radon concentrations in dwellings and workplaces has already been emphasized by the International Committee for Radiological Protection [8]. In that sense, schools are a particular case of a workplace for teachers and childcare workers, but they are also the environment where children spend most of their days besides home and the first place for social activities [9,10]. Furthermore, children are more susceptible to the carcinogenic effects of ionizing radiation than adults, including natural radiation [11], due to the morphometric differences between their lungs, as well as higher respiration rates [12].

Since radon exposure at schools was suggested to have a considerable impact on children's health, the interest in indoor radon monitoring in nursery and primary schools has been increasing [13–17].

Different instruments and techniques are available for radon detection and quantification [18]. Passive detectors have been used extensively due to their low price, simplicity, small size, lightweight and operation without risk of power loss, clogging or leaks [19]. Continuous detectors can measure radon concentrations continuously, but they are generally more expensive and bulky than passive devices, requiring power to operate [20]. Based on all these premises, along with the recent and revolutionary advances in sensing technology, a selection of low-cost, portable and "smart" (IoT enabled) sensor devices for continuous radon monitoring have been made commercially available [21]. These devices are emerging as promising technologies that will allow the end-user to measure indoor radon concentrations in real-time without needing an expert or being dependent on posterior laboratory analysis [21,22]. Despite these advantages, relevant uncertainties remain unclear regarding data accuracy and the ability for real-time response.

In order to use this commercially available, low-cost technology for radon monitoring and, consequently, to improve the indoor air quality, the present study mainly aimed to evaluate the performance of low-cost sensors devices for short-term continuous radon monitoring in the indoor air of nursery and primary school buildings in Porto (Portugal). Additionally, it intended to compare the evaluated performance between different occupancy statuses and between different age groups of the occupants (children).

2. Materials and Methods

2.1. Sampling Sites

This study was carried out in two school buildings—one nursery school (building A) and one primary school (building B), located in the metropolitan area of Porto, Northern Portugal (41° N, 8° W), a radon-prone urban area and directly influenced by traffic emissions. Specifically, one of the city's main roads with high traffic intensity [23] was less than 300 m from the two school buildings. Both buildings were representative of the most typical configuration of Portuguese school buildings: (i) Building A included classrooms for infants (under 3 years old) and pre-schoolers (3–5 years old); and (ii) building B included classrooms for pre-schoolers (3–5 years old) and primary school children (6–10 years old). Five representative classrooms of the different age groups were selected for this study, of which two were from the nursery school and three were from the primary school.

In addition, information on building and classroom characteristics, occupant density, activity patterns, timetables, ventilation and cleaning were collected. Table 1 summarizes the main characteristics of each studied classroom and respective building.

Both school buildings were initially built in the 1960s, which was long before the implementation of the first Portuguese legislation regarding indoor air quality (IAQ) (dated 2006), including a radon reference limit level (400 Bq/m^3). Since then, this legislation has been repealed, with the most recent being from 2021 (Portaria n.º 138-G/2021) [24], presenting a more restrictive radon reference limit level (300 Bq/m^3).

Both buildings have undergone significant renovations in recent decades, but the main structure was fully kept.

Most of the studied classrooms were located on the ground floor, except two classrooms (primary school children) that were located on the 1st and 2nd floors. In fact, in the typical configuration of a Portuguese school building, classrooms for younger children are often on the ground floor, while those for older children are on the upper floors. There was no mechanical ventilation in any of the studied classrooms, whereby natural ventilation was conducted by opening windows and/or doors throughout the day. Cleaning activities were usually carried out by cleaning staff more than once a day (during and after the occupancy period).

Table 1. Summary of the main characteristics of each studied building and classroom.

Building	Year of Construction	Room ID	Occupants' Age Group	Floor	Area (m^2)	Average Number of Occupants	Occupant Density ($\#/m^2$)	Occupancy Period
A	1960s decade (renovations in 1999)	A_I	Infants	GF	40	16	0.40	8:00–18:30
		A_P	Pre-schoolers	GF	65	20	0.31	9:00–18:00
B	1960s decade (renovations in 2006–2007)	B_P	Pre-schoolers	GF	40	18	0.45	9:00–18:00
		B_S1	Primary school children	1st	40	11	0.28	9:00–17:15
		B_S2	Primary school children	2nd	40	18	0.45	9:00–17:15

GF–ground floor.

2.2. Radon Monitors and Sampling

Radon indoor concentrations were continuously sampled (logging hourly means) using one research-grade instrument (considered the reference) and three low-cost-sensor radon monitors. The reference instrument was a Radim 5B radon monitor (SMM, Prague, Czech Republic), which measures the α-activity of radon decay products (218Po and 214Po) collected from the detection chamber on the surface of a semiconductor detector by an electric field. Radim 5B was factory calibrated according to the procedure previously described in Branco et al. [25]. The calibration precision was about 5%.

Three commercially available low-cost sensor devices for continuous radon monitoring were considered in the present study: Airthings Wave, RadonEye RD200 (RD200) and RadonEye Plus^2 (RD200P2). Table 2 summarizes their main characteristics, as well as the Radim 5B.

Table 2. Main characteristics of the three selected commercially available low-cost sensor devices and the reference instrument for continuous radon monitoring.

Device/Reference Instrument	Price (€)	Sensor Type	Measurement Range (Bq/m^3)	Minimum Time Resolution	Accuracy *	Internal Memory
Airthings Wave [26]	189	Passive diffusion chamber (using open photodiodes as semiconductor detectors)	0–20,000	1 h	<5–10% at 200 Bq/m^3 [a]	1.5 years
RadonEye (RD200) [27]	~200	Impulse-counting ionization chamber	7~3700	1 h	<±10%	1 year
RadonEye +^{2} (RD200 P2) [28]	~400	Impulse-counting ionization chamber	7~9435	1 h	±10%	1 year
Radim 5B [29]	3783	PIPS detector	0–50,000	1 h	5–20% [b]	7 years

* Accuracy indicated by the suppliers; PIPS—Passivated Implanted Planar Silicon; [a] <10% at 200 Bq/m^3 after 7 days and <5% at 200 Bq/m^3 after 2 months; [b] 5% for concentrations >80 Bq/m^3 and 20% for concentrations <80 Bq/m^3.

These devices were chosen based on a set of selection criteria that fit the purpose of radon monitoring in scholarly environments. Firstly, only commercial low-cost sensor devices for continuous radon monitoring available for purchase in the European Union were considered. Thus, the available options were greatly reduced, since there were few commercially available sensors devices for continuous radon monitoring, although there were studies that had developed their own [30–32]. Thus, only the devices that met the following criteria were considered: (i) The ability of continuous monitoring; (ii) the price was less than 400€; (iii) the limit of detection and the measurement range were appropriate for the expected ranges (which are known from previous studies [25,33]) and for the guideline values foreseen by Portuguese legislation and WHO; (iv) the privacy of data and location was ensured; (v) the ability of data acquisition and/or storage; (vi) simple connectivity options; and (vii) there was some graphical, numerical or visual indication of radon levels.

The three low-cost sensor devices used have different operation principles (a passive diffusion chamber in Airthings Wave and a pulsed ion chamber in both RadonEye versions). They also have different measurement ranges. Moreover, all the devices require a smartphone/tablet supporting Bluetooth Low Energy (BLE) for communication and data acquisition. According to the information provided by the suppliers, data privacy is guaranteed in all procedures, from the collection and use to storage and transfer.

Radon monitoring was carried out using both reference and low-cost equipment simultaneously, for a short-term period varying from 2 to 4 consecutive days in each studied classroom, including weekdays and weekends. Table 3 shows the sampling dates and the number of consecutive sampling days in each studied classroom. All equipment was deployed side-by-side on a table or a shelf, as close to the center of the room possible, far from windows and doors, and at the approximate height of children's breathing (1.25 $\pm$ 0.5 m).

Table 3. Dates of sampling and the respective number of consecutive sampling days.

Room ID	Date of Measurements	Sampling Days
A_P	6–8 April 2021	2
A_I	8–12 April 2021	4
B_S2	19–23 March 2021	4
B_P	23–25 March 2021	2
B_S1	13–15 April 2021	2

2.3. Data Analysis

Radon concentrations were collected from low-cost and reference equipment at the five studied classrooms for analysis. Thus, continuous measurements logged each hour allowed us to calculate descriptive statistics of radon concentrations in each device, namely the minimum, maximum, mean, median and plot time-series. The performance of the three low-cost sensor devices for continuous radon monitoring was evaluated with two performance indices—R^2 and root mean square error (RMSE)—considering the calibrated Radim 5B as the ground truth. Moreover, for additional comparisons, two periods were considered according to the occupancy statuses of the room, namely: (i) The entire period (considering all the data logged in each classroom); and (ii) the occupancy period (considering only the data logged when the room was occupied according to the school timetable, summarized in Table 1). All statistical analyses were performed using MS Excel® (Microsoft Corporation, Redmond, WA, USA).

3. Results and Discussion

Table 4 summarizes the main descriptive statistics (minimum, maximum, mean and median) of the hourly radon concentrations from Radim 5B, Airthings Wave and both RadonEye versions (RD200 and RD200P2), in both studied periods (entire period and occupancy period) and each studied classroom of the two school buildings. Figure 1 shows time-series plots of radon concentrations in all studied classrooms in both buildings.

Table 4. Descriptive statistics of the hourly radon concentrations from Radim 5B, Airthings Wave and both RadonEye versions (RD200 and RD200P2), in both studied periods (entire period and occupancy period) in each studied classroom.

		Entire Period				Occupancy Period			
Room ID		**Radim 5B**	**Wave**	**RD200**	**RD200P2**	**Radim 5B**	**Wave**	**RE**	**RD200P2**
A_P	min	2.8	10.0	25.0	2.0	2.8	12.0	25.0	2.0
	max	473.1	52.0	611.0	522.0	180.2	26.0	286.0	307.0
	mean	152.9	21.5	171.2	137.4	59.3	16.5	79.3	67.2
	med	121.1	16.0	135.0	105.5	49.3	15.5	47.0	39.5
A_I	min	0.0	8.0	19.0	0.0	0.0	220.0	19.0	0.0
	max	757.5	554.0	910.0	1181.0	149.2	515.0	119.0	276.0
	mean	391.5	333.1	489.4	517.9	48.0	330.3	51.7	57.7
	med	492.8	374.0	596.0	601.0	47.9	243.0	49.0	39.0
B_S2	min	0.0	18.0	35.0	11.0	0.0	59.0	35.0	14.0
	max	183.0	83.0	213.0	195.0	152.1	68.0	139.0	175.0
	mean	83.9	57.4	104.5	75.7	48.2	64.0	66.6	49.9
	med	80.3	63.0	99.0	75.0	45.1	65.0	65.0	33.0
B_P	min	0.0	52.0	19.0	7.0	0.0	64.0	27.0	9.0
	max	191.5	80.0	195.0	152.0	92.9	80.0	99.0	57.0
	mean	75.8	66.5	92.7	63.3	35.9	73.1	49.4	24.0
	med	78.8	67.0	92.5	51.0	28.2	75.0	41.0	19.0
B_S1	min	0.0	13.0	29.0	5.0	0.0	30.0	29.0	5.0
	max	149.2	51.0	187.0	141.0	70.4	42.0	63.0	44.0
	mean	65.3	33.8	85.9	53.3	34.7	35.9	40.6	18.4
	med	62.0	36.0	76.0	45.5	36.6	36.0	41.0	15.0

Wave—Airthings Wave; RD200—RadonEye RD200; RE200P2—RadonEye Plus^2.

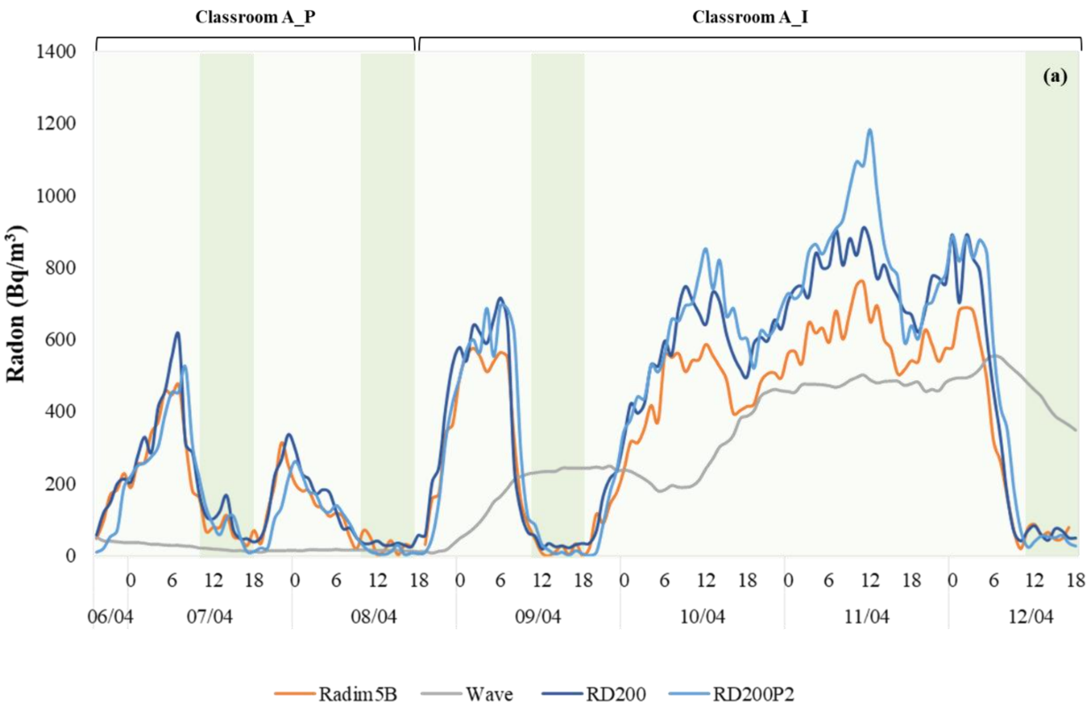

Figure 1. *Cont.*

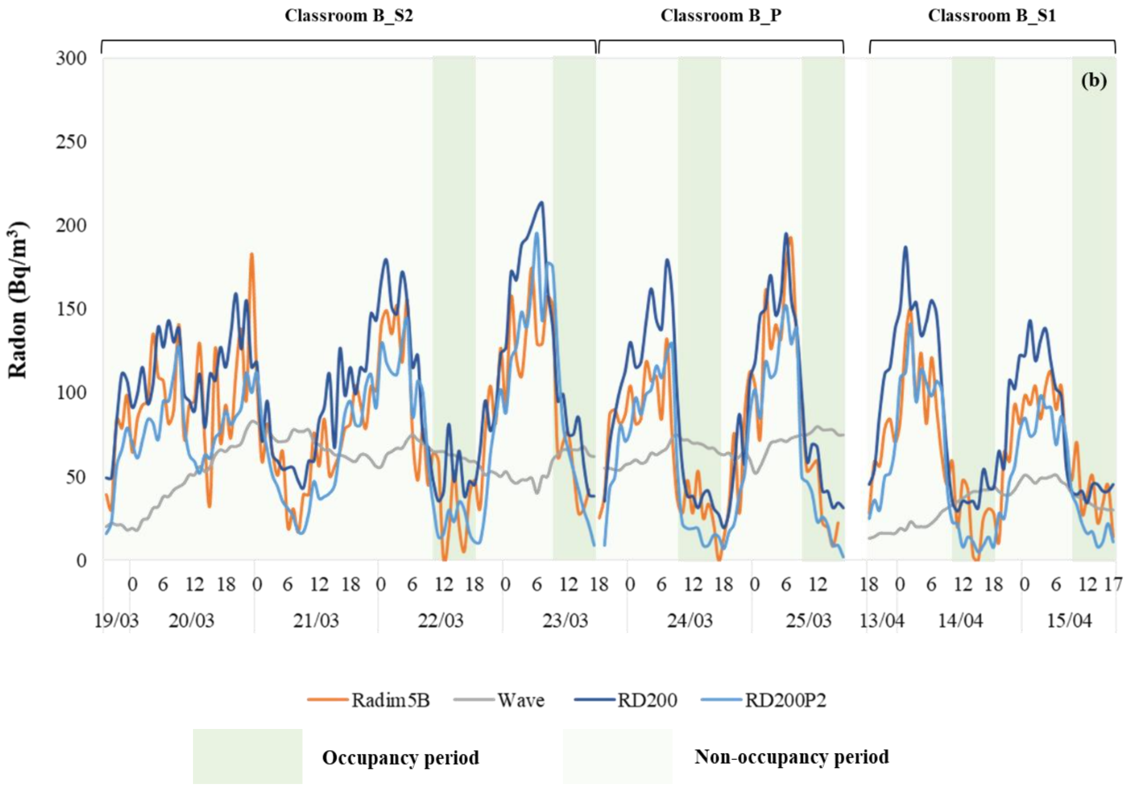

Figure 1. Time-series plots of radon concentrations in all studied classrooms from (**a**) Building A and (**b**) Building B.

As can be seen in Figure 1 and Table 4, radon concentrations were generally higher on weekends than on weekdays, especially when compared with the occupancy periods. Thus, a typical profile was established, characterized by an increase in the indoor radon concentration at the end of the day (after closing schools), resulting in higher concentrations during the night, followed by a decline throughout the day (coincident with the reopening of the schools). Occupancy and ventilation patterns seemed to be responsible for those profiles, with the higher concentrations during the weekend and non-occupancy periods caused by the lack of air renewal (leading to radon accumulation); and with the lower concentrations along the occupancy period due to the increase in natural ventilation (promoting air renovation with air from outdoors free from radon). These patterns are in accordance with the typical daily patterns found in other studies carried out in school buildings [25,33–35]. The reference instrument (Radim 5B) and both RadonEye low-cost sensor devices obtained similar profiles. On the other hand, the Airthings Wave behaved quite differently from all the other radon-monitoring devices studied (reference and low-cost). This device had a smoother profile, different from the reference Radim 5B, not detecting short-term peaks or even higher concentrations. Such difference may be related to the method/principle of operation used by this device (a passive diffusion chamber), which is different from the other devices (a pulsed ion chamber) and requires seven days of initial warm-up.

Although similar profiles were observed, the highest concentration was generally detected by low-cost sensor devices, namely in classroom A_I from building A during the weekend (1181 Bq/m^3-RadonEye Plus^2). Both classrooms from building A presented higher concentrations than classrooms from the other building. Although both buildings were constructed in the same decade, building B underwent more recent renovations, probably using materials and techniques that better prevent radon from entering the building from its foundations, which could explain the lower concentrations compared to building A. Moreover, the two RadonEye low-cost sensors devices overestimated the radon concentrations in classroom A_I, mostly during non-occupancy periods, which was not critical from the point of view of children's exposure. The reference limit value for radon in the Portuguese legislation (300 Bq/m^3) [24] was never exceeded during the occupancy period. Exceedances were found in two classrooms from building A during non-occupancy. Moreover, some exceedances to the action limit level foreseen by WHO (100 Bq/m^3) [36] were found, including during occupation in classroom A_P.

Children attending classrooms in building A, where radon levels were found to be the highest, were even more susceptible to radon exposure. Since radiation effects take years to manifest, radon-related illnesses appear later in life [37]. Being the youngest children exposed to high radon levels, they are more likely to acquire these illnesses earlier in life. Furthermore, children have higher breathing rates, with nearly double the chance of developing lung cancer compared to adults [38]. In fact, in a nationwide survey of radon levels in the USA, almost one out of five schools had at least one classroom with high radon levels [12]. According to USEPA [37], more than 70,000 classrooms have elevated short-term radon levels. There is no known safe level for radon exposure, even for a short-term period [39], so testing and reducing radon levels to the minimum possible should be pursued as a continuous practice in schools. Table 5 summarizes the performance indices considered (R^2 and RMSE) resulting from comparing each low-cost sensor device and the reference instrument (Radim 5B).

Table 5. R^2 and RMSE results from comparing each low-cost sensor device and the reference instrument (Radim 5B) during the entire period and occupancy period.

Room ID	Device	R^2		RMSE	
		Entire Period	Occupancy Period	Entire Period	Occupancy Period
A_P	Wave	0.173	0.679	177	62.5
	RD200	0.878	0.832	52.6	36.9
	RD200P2	0.726	0.795	71.6	43.9
A_I	Wave	0.0877	0.0625	244	301
	RD200	0.961	0.771	127	20.1
	RD200P2	0.924	0.559	176	46.7
B_S2	Wave	0.0277	0.0133	34.9	25.5
	RD200	0.614	0.446	24.5	26.1
	RD200P2	0.631	0.623	23.2	18.7
B_P	Wave	0.0305	0.0928	53.2	42.6
	RD200	0.746	0.482	34.5	21.6
	RD200P2	0.778	0.391	27.6	20.8
B_S1	Wave	0.0102	0.0455	49.6	19.5
	RD200	0.717	0.0196	32.1	19.7
	RD200P2	0.770	0.330	21.8	22.1

Wave—Airthings Wave; RD200—RadonEye RD200; RE200P2—RadonEye Plus^2.

From Table 5, it was possible to observe that both RadonEye devices performed better (better R^2 and RMSE) than the Airthings Wave. However, there are no evident differences between the RD200 and RD200P2. In turn, the Airthings Wave presented only a weak to moderate performance, with R^2 varying between 0.0102 and 0.679 and RMSE > 19.5 Bq/m^3. These results reduce the confidence in using Airthings Wave as a reliable indicator of indoor air radon in short-term monitoring. This device requires a seven-day initial warm-up [26], which was not implemented in this short-term campaign (<5 days in each classroom).

Generally, the performance of all the studied low-cost sensor devices, particularly both versions of the RadonEye device, was better during the entire period than when considering only the occupancy period (which is coincident with the lowest concentrations registered). The classrooms with higher radon concentrations—classrooms A_I and A_P—presented the best R^2 considering the entire period (R^2 = 0.961 and R^2 = 0.924

for RD200 and RD200P2, respectively, in classroom A_I and R^2 = 0.878 and R^2 = 0.726 for RD200 and RD200P2, respectively, in classroom A_P), but also the highest errors (RMSE = 127 Bq/m^3 and RMSE = 176 Bq/m^3 for RD200 and RD200P2, respectively, in classroom A_I and RMSE = 52.6 Bq/m^3 and RMSE = 71.6 Bq/m^3 for RD200 and RD200P2, respectively. in classroom A_P). Contrarily to what happened with the Airthings Wave device, these results seem to indicate that the RadonEye low-cost sensor devices can be used in short-term radon monitoring, being able to detect peak concentrations. Given their low cost and graphical interface (concentrations displayed in a built-in screen or an online dashboard), they can be considered for use in multiple-site testing (for example, sampling several rooms of the same building at the same time), as well as for providing reliable real-time results. In addition, it is expected that the performance of these low-cost sensor devices would improve when applying an ad-hoc calibration methodology [40,41].

Still, a long-term evaluation should also be considered in the future to assess the performance of the three tested low-cost sensors devices for long-term radon monitoring (3 months to 1 year). Those devices that performed better in short-term monitoring (RadonEye versions) may not be the best when considering long-term monitoring. Alternatively, a follow-up study in a different season can be considered to support short-term radon analysis. When considering long-term performance evaluation, passive radon detectors (dosimeters) should also be considered for comparison, including CR-39 solid-state nuclear track detectors and/or LR-115 films as they are more commonly used for long-term radon sampling [42]. Given the high radon concentrations registered and considering the characteristics of each building and respective classrooms, customized and individual mitigation measures should be defined and applied to lower radon concentrations, thus reducing occupants' exposure and health risks. These measures could be cost-free and straightforward, such as increasing natural ventilation (especially before and during occupancy periods), or more complex and expensive when ventilation is insufficient and/or inefficient, such as installing a sub-slab depressurization system [43]. Furthermore, low-cost sensor devices for continuous radon monitoring could be used to inform occupants about the radon concentrations in real-time, thus supporting the decision for action and the best mitigation measure to apply. Alvarellos et al. [32] developed low-cost continuous radon monitoring based on a commercially available Radon Eye RD200M version and a complementary alert system. They concluded that this approach (continuous radon monitoring with a system alert) could be appropriate and satisfactorily used to lower radon levels in indoor air. Bayrak et al. [31] designed, produced and tested a low-cost radon detection system (a radon monitor) in campus buildings of the Istanbul Technical University, advancing its use for the production of radon maps of wider regions in short periods, as well as for the purpose of monitoring radon activities and also integration into the air circulation system of the buildings to track the air quality.

Although this study is still a preliminary approach, it was possible to identify two main limitations: (i) The seven days of warm-up foreseen for the Airthings Wave was not carried out (since it was for short-term measurements); and (ii) the number of classrooms and schools assessed was limited and should be extended.

4. Conclusions

To the authors' knowledge, this was the first study evaluating the performance of commercially available low-cost sensors devices for continuous radon monitoring in the indoor air of nursery and primary schools.

The present study concluded that, in schools, the studied RadonEye low-cost sensor devices (RD200 and RD200P2) had behavior similar to the reference instrument (Radim 5B), while the Airthings Wave behaved differently. Accordingly, RadonEye devices presented better performance indices (R^2 and RMSE) than the Airthings Wave, both during the entire period and considering only the occupancy period. Thus, these RadonEye devices seemed to be more suitable for real-time short-term radon monitoring, detecting peak concentrations with high accuracy. Although the reference Portuguese legislated limit value for radon was only exceeded in two classrooms (from building A), several exceedances to the action limit level foreseen by WHO were found. In that sense, these low-cost sensors devices for continuous radon monitoring could be used as a tool to reduce indoor radon throughout the active application of near real-time mitigation measures, e.g., the opening of a window. Future studies should include more classrooms and schools, and the same evaluation should be extended to long-term monitoring and compared with passive radon detectors. Additionally, an ad-hoc advanced calibration strategy should be developed and applied to improve data accuracy.

Author Contributions: J.P.S. contributed to the study design, collected field data, performed the statistical analysis, interpreted the results and drafted the manuscript. P.T.B.S.B. contributed to the study design and to the results' analysis and interpretation and critically revised the manuscript. M.C.M.A.-F. and F.G.M. contributed to the design of the study and critically revised the manuscript. S.I.V.S. conceived the study, led the study design and coordination, contributed to the interpretation of the results and critically revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by LA/P/0045/2020 (ALiCE) and UIDB/00511/2020-UIDP/00511/2020 (LEPABE) funded by national funds through FCT/MCTES (PIDDAC); Project PTDC/EAM-AMB/32391/2017, funded by FEDER funds through COMPETE2020–Programa Operacional Competitividade e Internacionalização (POCI) and by national funds (PIDDAC) through FCT/MCTES. Sofia I.V. Sousa thanks the Portuguese Foundation for Science and Technology (FCT) for the financial support of her work contract through the Scientific Employment Stimulus Individual Call CEECIND/02477/2017.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to the nursery and the primary schools involved in this study.

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

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