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Children's Exposure to Radon in Schools and Kindergartens in the Republic of Moldova

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Abstract: This work presents the results from measurements of radon concentrations in primary and high school education institutions—including their gymnasiums—from the Chisinau municipality and various rayons from the central and southern part of the Republic of Moldova. In the research carried out during the years of 2013–2014 and 2021, there were 78 (29 + 49) premises included, respectively, and 149 and 23,805 investigations were performed using RTM-1642 (active measurements) and RadonEye^{+2} devices (passive measurements). The results show an essential variability for the studied radio-stressogenic factor, depending on the geological conditions of the location of the premises and the age of the building. Thus, during 2013–2014, the minimum concentration of radon detected was 26 Bq m^{-3}, and the maximum detected was 607 Bq m^{-3}. In 2021, the results denote an indicator variability in the range of 17.4–657.9 Bq m^{-3} for early education institutions, with an average value of 127.6 Bq m^{-3}, and denote a range of 231.8–1129.3 Bq m^{-3}, with an average value of 665.4 Bq m^{-3}), for high school education institutions and their gymnasiums. The effective annual dose for the children in a classroom varies between an interval of 0.21–4.88 mSv y^{-1} (average 1.19 mSv y^{-1}) and 0.14–9.08 mSv y^{-1} (average 1.29 mSv y^{-1}) for the 2013–2014 and 2021 surveys, respectively.

Keywords: radon; risk assessment; schools and kindergartens; Republic of Moldova

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1. Introduction

Radon (Rn) is a radioactive natural gas found in the Earth's crust. Radon is part of a long chain of radioactive decay that begins with uranium, which has been present in rocks and soil since the Earth was formed. Radon cannot be perceived by humans, as it is colorless and odorless, but it can be measured due to its radioactivity. It is absorbed inside dwellings from the soil. In some dwellings, high concentrations of radon are recorded, especially in areas with a greater amount of natural uranium in the soil and rocks. Radon may also be present in building materials and drinking water, but, in most cases, it causes less radiation exposure than soil radon [1–3].

Exposure to natural radioactive sources is primarily due to radon—about 50% of the dose formed [1]. Radon is continuously produced by uranium present in rocks. Once the radon is emitted, it migrates to the soil surface through the pore spaces in the soil. Radon can enter buildings due to the difference in pressure between the building and its foundation in the soil, especially through cracks in the walls, drains, communication pipes, building materials, and drinking water [4,5]. The accumulation of radon inside buildings is a consequence of technological progress. Insulation work, tightly closed windows, and poor ventilation of the rooms lead to an unnoticed increase in the concentration of radon inside. To determine the level of radon in a particular room, it is necessary to measure the concentration of radon in the indoor air. Radon is often measured using small plastic detectors, which are placed in the dwelling for several weeks to properly measure the average concentration of radon [3]. The main sources of radon in the dwelling are in order of importance: exhalation of radon from the soil, emanation from the construction materials of the dwelling, water used for washing and cooking, as well as gas used in kitchens or stoves for heating [5,6].

Prolonged exposure to radon inside the rooms increases the risk of lung cancer. In its report on radon in buildings [5], the World Health Organization (WHO) highlights that it is the leading cause of lung cancer in non-smokers. The risk increases depending on the duration of exposure to radon, being dependent on both the concentration of radon inside and the time of exposure. Only systematic exposure to high concentrations of radon poses a health hazard. Total exposure to radon consists of exposure in rooms, at school, at work, and during leisure time, which is crucial. It is well known that exposure to excessive levels of radon is a significant cause of lung cancer [7,8]. Lung cancer is a multifactorial disease with multiple risk factors, including exposure to radon inside buildings. While tobacco is the main risk factor for developing lung cancer, radon in buildings is the second leading cause of lung cancer in the general population. Bronchopulmonary cancer is one of the most significant human neoplasia in terms of incidence and mortality. The highest standardized rates of lung cancer incidence worldwide are found in North America and Europe (WHO, 2012) [7]. Epidemiological and ecological studies have confirmed that radon in homes increases the risk of lung cancer in the general population [3,9–14].

The significant variability of the volumetric activity of radon in the indoor air is mainly due to the geology of the territory and factors affecting the pressure difference outside and inside the building, such as the air exchange rate and building heating and weather conditions [14]. While the concentration of radon released from the soil quickly dilutes in the outside air, this does not happen in enclosed spaces and, depending on the rate of ventilation, the gaseous radon can accumulate in the building [15,16]. In a number of cases, the exposure of the population to radon in housing leads to annual values of the effective dose exceeding the dose limit for people working professionally with ionizing radiation.

The International Agency for Research on Cancer (IARC) classified radon as a human lung carcinogen as early as 1988 [17]. The International Commission for Radiological Protection (ICRP) has approved the Radon Declaration for the revision and updating of additional guidelines on the control of exposure from radiation sources [14]. In light of these publications, the International Atomic Energy Agency (IAEA) (2012) [17] and the European Commission (2013) [18] have revised their Basic Safety Standards. Both safety standards have a requirement for controlling the public's exposure to indoor radon. Epidemiological studies carried out in residential premises directly confirm the risk of lung cancer through exposure to radon, as well as non-cancerous diseases of the upper respiratory system and cardiovascular diseases [5,19–21].

The monitoring and control of the concentration of indoor radon in housing and workplaces is a very important issue worldwide. In this respect, kindergartens are considered a priority: they are jobs and a place to live at the same time [17]. Radon is most dangerous for children because of the diminished resistance of the child's body. Furthermore, children spend more time indoors and are generally more sensitive to exposure to environmental hazards, including ionizing radiation [22,23]. The risk of lung cancer in children as a result of exposure to radon can be up to three times higher than that of adults exposed to the same amount of radon due to morphometric differences between the lungs of children and the lungs of adults, as well as the higher breathing rates of children compared to adults. Thus, knowledge of harmful radon levels in kindergartens and schools is an obvious goal for all of us.

Many published studies and reviews were focused on the radon measurements in the indoor air of schools and kindergartens or nurseries using special protocols [24–40]. To investigate the influence of different factors on indoor radon concentrations, most studies considered measurements at different locations and different floor levels inside buildings; moreover, some authors have also taken into account other factors such as the type of use, the age of the building, building materials, building improvements, and different geographical contexts (rural vs. urban). In several EU countries, radon concentrations higher than the reference levels applied in the respective country were reported [26–29].

The determination of the concentration of radon in the air in public buildings, including primary, secondary, and high school education institutions, is a priority action for the elaboration and implementation of the action plan of radon exposure control in the context of the objectives of Euratom Directive 59/2013 [19] and of the draft law on basic requirements in radiological security in the Republic of Moldova [41].

Several studies in the Republic of Moldova dealt with the measurements and evaluation of the radon dose in indoor spaces such as residential houses, public places, and workplaces [3,42,43].

The purpose of this work was to study the levels of radon concentration and annual effective dose due to exposure to radon in the air of children's educational institutions in the territory of the Republic of Moldova and to identify the buildings where it is necessary to take measures to reduce the concentration of radon.

2. Materials and Methods

2.1. Study Area

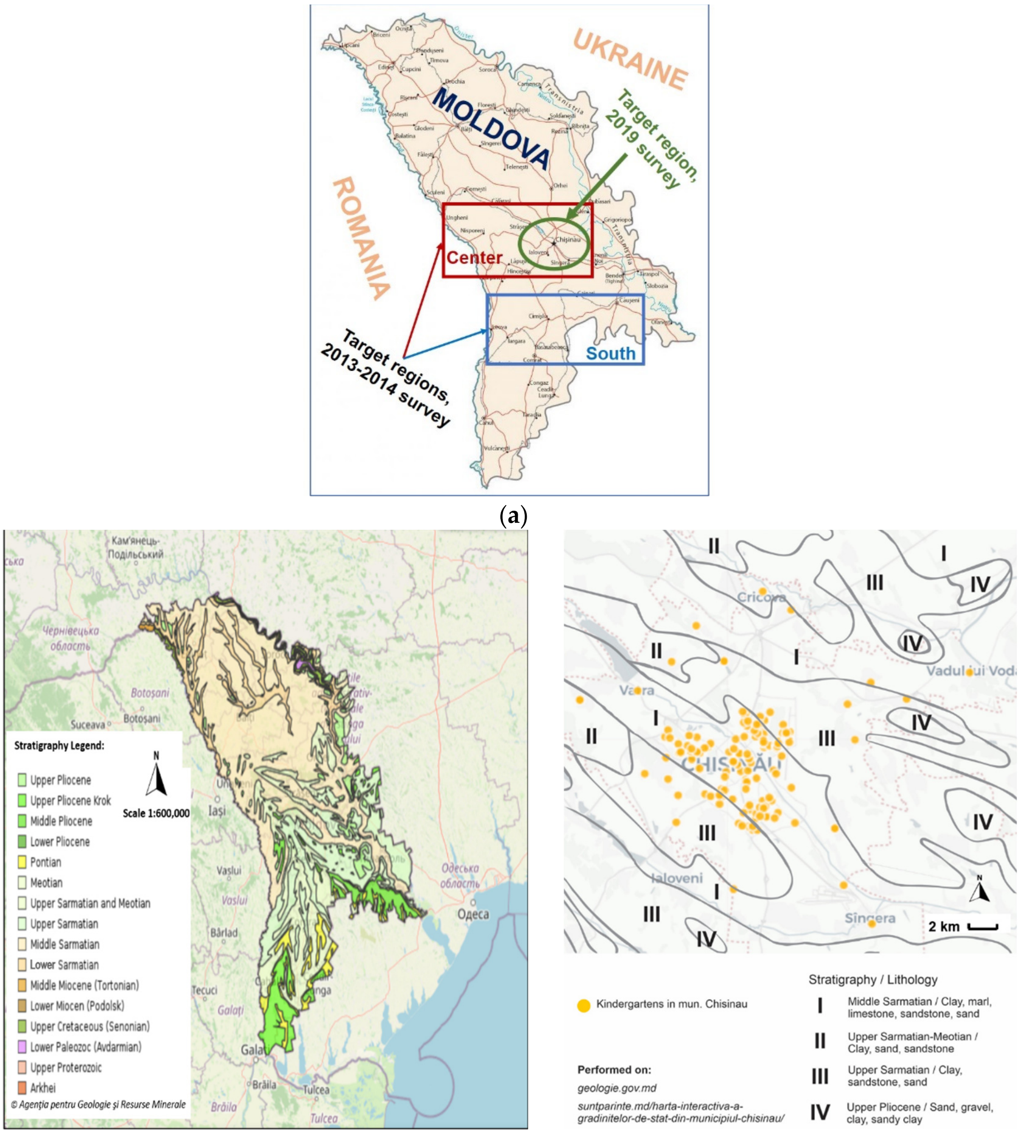
The concentration of radon was measured in the air of public buildings in the Republic of Moldova, wherein most were kindergartens, and some high schools/gymnasiums were included, over the course of two campaigns: 2013–2014 (preliminary, screening survey) and 2021 (complex survey).

The measuring points of the concentration of ^{222}Rn in the indoor air were directly selected from the list of educational institutions in the radius of Chisinau municipality and other rayons. Localities from the central part of Moldova (Ungheni, Criuleni, Ialoveni, Hâncești rayons, and Chisinau municipality) and the southern part (Căușeni, Leova, Comrat rayons) were included in the study (Figure 1a).

The localities for studying the radon concentration were selected based on the fact that studies of the incidence/prevalence of bronchopulmonary cancer in the territory of the Republic of Moldova, according to the National Registers, demonstrated an increase in the mentioned indicators (absolute cases) for the central zone of the country, including the municipality of Chisinau [3]. In this regard, we have intensified the indoor radon measurements in these localities during the 2021 survey, especially in schools and kindergartens—independent of various conditions and external factors—and research is ongoing for this region.

The studied area is located in the central part of a geological structure in southeastern Europe, the base of which consists of granite slabs and gneisses from the archaic era, located at a depth of 1150 m below sea level (Figure 1b,c). The upper part of the geological section of this structure is represented by sedimentary rocks from the Silurian, Devonian, Paleogene, and Neogene eras. In the erosive section there is lithology of clay, marl, gravel, limestone, sandstone, and sands from the Upper Cainozoic (Middle Sarmatian, Upper Sarmatian, and Upper Pliocene stratigraphy). From north to south the area is intersected by a layer of mid-Sarmatian reefs [44].

The soils in the localities where the investigations were carried out are loamy (45%) and sandy (55%) chernozems [44].



(**a**)

(**b**) (**c**)

Figure 1. (**a**). Map of the studied areas in the Republic of Moldova; (**b**) Geological map of the Republic of Moldova (available on-line [44]); (**c**) Geological map of the Chisinau region and distribution of the target buildings in the 2021 survey.

2.2. Characteristics of the Buildings

Usually, children's institutions (both schools and kindergartens) are located in 1–3 large, separate buildings—either with or without basements—that are especially built or reconstructed for education and youth care purposes. Buildings differ substantially in age, size, type of building materials, or type of construction. They have different types of heating systems, either being connected to local central heating systems or possess individual systems. There are also different air conditioning systems. The majority of measurements (80%) were taken in bedrooms and play/study rooms on the first floor, where children spend most of their time in institution. The majority of the buildings of educational institutions were built more than 20 years ago from limestone blocks, and the basements were built from reinforced concrete. The characteristics of the investigated premises in the two surveys, together with the physical factors, are presented in Table A1 (2013–2014 survey) and Table A2 (2021 survey), Appendix A.

2.3. Radon Analysis and Dose Assessment

Most of the measurements, made with active detectors RTM-1642 purchased from the company SARAD, Dresden, Germany, were performed during the summer (2013–2014); for screening measurements, the exposure period was 3–4 h. Subsequently, in the year 2021, the measurements of radon concentrations in educational institutions were carried out using RadonEye^{+2} devices with passive radon recording detectors, which were from the company RADONOVA, Uppsala, Sweden, and were purchased within the technical cooperation project with IAEA MOL9007; they were placed for a median period of 20 days on the ground floor. Radon measuring devices were deployed in public kindergartens distributed over the Chișinău municipality (47°13′ N and 28°54′ E) and the Ialoveni rayon (46°50′ N and 28°50′ E), which are located in the center of the Republic of Moldova (Figure 1c).

A total of 78 buildings were included in the research for testing, with 29 of them being tested with the RTM-1642 device (Table A1, Appendix A) and 49 being tested with RadonEye^{+2} (Table A2, Appendix A). In total, 149 investigations (30 min each) were carried out with the RTM-1642 device and 23,805 investigations (1 h each) with RadonEye^{+2}. The passive detectors were installed at least 1 m above the floor and at least 0.5 m from the walls and any surrounding objects, as well as away from children.

The analysis and processing of the results were carried out in the Laboratory of Radiation Hygiene and Radiobiology of the National Agency for Public Health, according to the guide, "Methodology of Radon Monitoring in Early Education Institutions and Primary, Secondary, and High School Education Institutions", and was approved by the Order of the Ministry of Health of the Republic of Moldova no.1344 on 26 November 2018 [45]. Finally, all the data were extracted from the device with the RadonEye^{+2} program and compiled in Microsoft Excel 2019. A statistical analysis was carried out with Statistica-10 software.

The annual effective dose due to indoor radon gas exposure, E (mSv y^{-1}), is given by Equation (1) proposed by ICRP 137 [46]:

$$E = C \times T \times DCF \quad (1)$$

where C is the radon concentration (in Bq m^{-3}), T is the occupancy time (h y^{-1}) in the premises, and DCF = 6.7×10^{-6} mSv (Bq h m^{-3})$^{-1}$ is the dose conversion factor for a working place, assuming an equilibrium factor of 0.4 between radon and its daughters.

3. Results and Discussion

3.1. Radon Concentrations in Studied Pre-University Institutions in Republic of Moldova

During the period of 2013–2014 in the Republic of Moldova, a total of 149 investigations of radon concentrations in 29 early education institutions and primary, gymnasium, and high school education institutions were carried out with the RTM 1642 device based on active radon recording detectors located at different levels in the buildings in the following rayons/districts (R): Ungheni, Causeni, Leova, Criuleni, Ialoveni, Hancesti, and Comrat (Table A1—Appendix A and Figure 2). The localities cover the central and southern areas of the country. The results show that in the central part of the republic, the concentrations of radon in early education institutions and primary, gymnasium, and high school education institutions varied within the limits of 26–607 Bq m^{-3}, while in the south, the range was between 48–210 Bq m^{-3} (Table A1—Appendix A). Thus, we can state that in the central and southern parts of the republic, the values of the concentration of radon exceeded the permissible national norms. Higher values of radon concentrations were detected in early education institutions and primary, secondary, and high school education institutions in the central region of the republic. Our results (Figure 2) demonstrate that in the rooms located on lower floors (basement, ground floor), the radon concentration is higher than on the first or second floor, which is a result of the closeness of these lower floors to the main source of radon—the soil— a trend that is supported by other studies [2,29,33,34]. On these premises, remedial measures have been proposed to remedy radon concentrations in order to not exceed the levels of 100/150 Bq m^{-3} in new and old buildings, respectively, according to the old national norms.

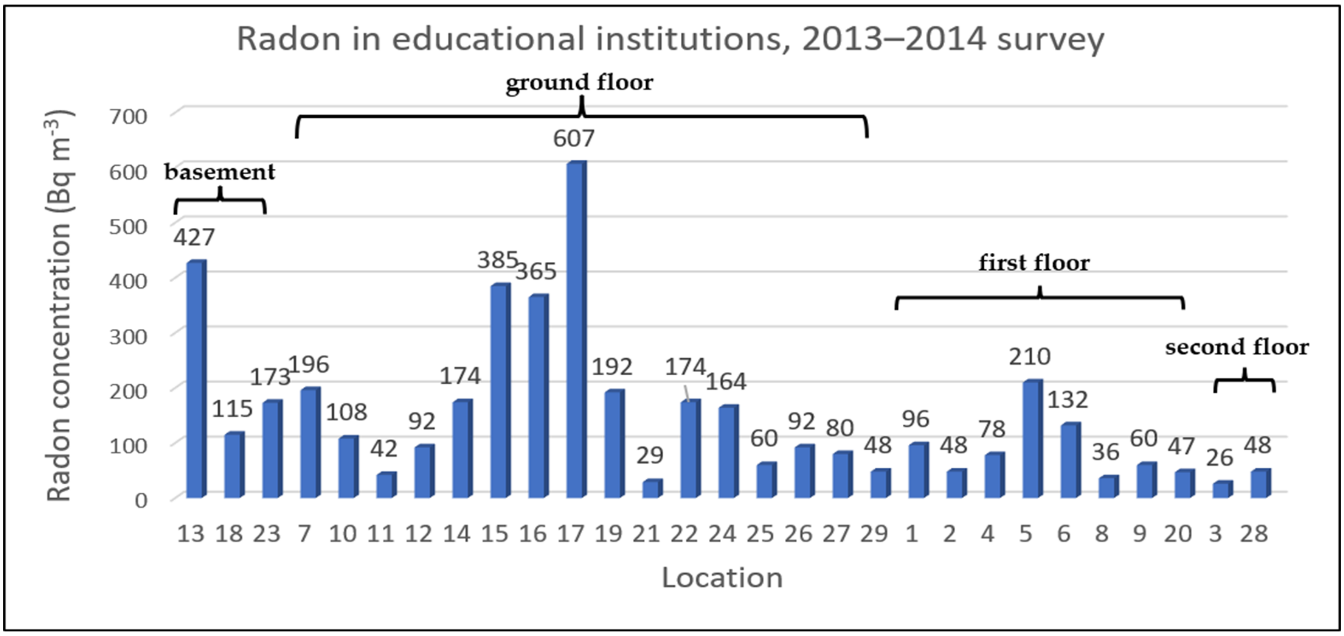


Figure 2. Distribution of radon concentrations in educational institutions of Republic of Moldova during the period of 2013–2014.

From Table 1 it can be seen that the average concentration of radon in the educational institutions investigated during the period of 2013–2014 in the territory of the Republic of Moldova was 150.1 Bq m^{-3}, and in early education institutions it was 147.1 Bq m^{-3}. Taking into account that most of the buildings investigated were of an older age, we can admit that the detected values of the radon concentrations were within the national norms, which is stipulated in the normative acts.

Table 1. The average concentration of radon in early education institutions and primary, gymnasium, and high school education institutions in the territory of the Republic of Moldova during 2013–2014.

No	The Location of the Measurements	Number of Institutions	Number of Measurements	Average Concentration of ^{222}Rn, Bq m^{-3}
1	Primary, gymnasium, and high school education institutions	13	62	150.1
2	Early childhood education institutions	16	87	147.1

In 2021, the determination of radon concentrations in indoor air was carried out in 49 early education institutions, as well as secondary and high school training institutions in Chisinau and Ialoveni rayon, a district nearby Chisinau (Table A2—Appendix A), with 23,805 investigations being performed with RadonEye^{+2} passive detector devices. The distribution of radon concentrations in the indoor air of educational institutions that were investigated in 2021 is presented in Figure 3. The statistical analysis shows a variation of the indicator in the range of 17.4–657.9 Bq m^{-3} for early childhood education institutions (the average value being 127.6 Bq m^{-3}) and 231.8–1129.3 Bq m^{-3} for secondary/high school education institutions (with an average value of 665.4 Bq m^{-3}).

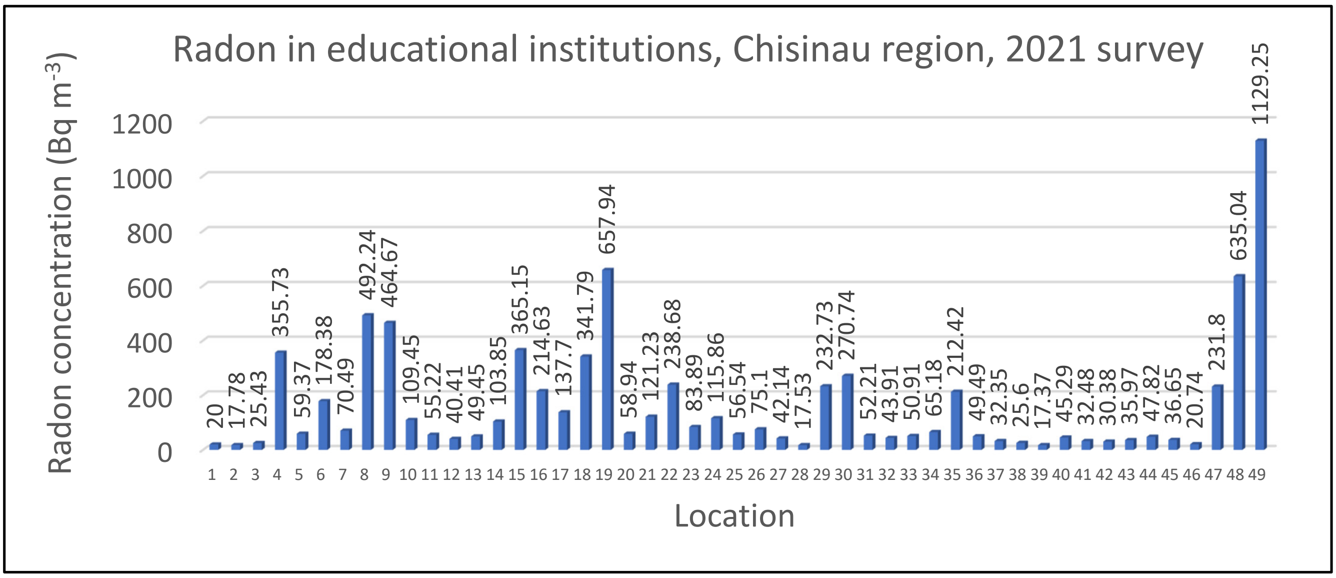


Figure 3. Distribution of radon concentrations in educational institutions in the Republic of Moldova, Chisinau region, during the 2021 survey.

By comparison with the concentration of radon in the air of the dwellings, where the indicator varied within the limits of 51.55–728.38 Bq m^{-3}—the average value being 242.37 Bq m^{-3} [47]—it was proved that in the educational institutions, the index was lower, which can be explained by the use of additional fans on the mentioned premises. At the same time, it should be mentioned that for the underground galleries used for storing wines from Cricova and Mileștii Mici, the indicator varied within the limits of 26.61–813.8 Bq m^{-3}, with the average value being 359.14 Bq m^{-3} [47].

The descriptive statistics of the data obtained in this work during the two surveys are presented in Table 2, along with the results reported in the literature for other countries.

Table 2. Descriptive statistics of indoor radon measurements (in Bq m^{-3}) in educational institutions from different European countries.

Country (Region)	Min	Max	Median	AM	SD	GM	GSD	Reference
Republic of Moldova (center and south)	26	607	96	148.4	137.8	105.2	2.27	This work, 2013–2014 survey
Republic of Moldova (Chisinau)	17.4	1129.3	59.4	160.6	213	86	2.94	This work, 2021 survey
Romania (Cluj)	23	460	97	141	124	99	-	[2]
Romania (3 counties)	31	414	-	215	-	-	-	[48]
Bulgaria (Sofia)	9	1415	98	132	118	101	2.08	[27]
Bulgaria (Kremikovtsi)	32	1305	196	339	315	220	2.59	[4]
Hungary	16	160	56	61	29	54	-	[26]
Czech Republic	204	1500	-	177	-	124	2.25	[25]
Finland (schools)	-	4205	41	82	-	42	-	[28]
Finland (daycare centers)	-	2426	40	86	-	39	-	[28]
Greece (8 regions)	60	958	135	149	-	126	-	[32]
Portugal (Porto, NE)	56	889	154	197	144.1	-	-	[34]
Italy (Salento)	65	1808	179	292	309	215	65	[31]

Table 2. *Cont.*

Country (Region)	Min	Max	Median	AM	SD	GM	GSD	Reference
Italy (South)	11	1416	74	98	-	77	2	[35]
Macedonia (Eastern)	10	508	-	136	115	96	2.47	[36]
Montenegro	16	2810	169	275	324	174	2.58	[37]
Latvia (kindergartens)	1	287	48	62.75	46.75	-	-	[38]
Latvia (schools)	10	460	59	88.49	80.26	-	-	[38]
Serbia (Nis)	15	256	-	59.7	25.3	-	-	[39]
Serbia	17	428	96	118	78	97	1.9	[49]
Poland (Kalisz)	5	194.4	31.5	46	45	30.3	2.48	[50]
Poland (Ostrów Wielkopolski)	5	216.8	26.9	48.9	49	29.8	2.86	[50]
Austria	-	11000	61	102	-	75	3.10	[51]
Slovenia	145	794	-	-	-	-	-	[30]

For the two surveys, the radon concentration distributions show a median value of 96 Bq m^{-3} and 59 Bq m^{-3}, respectively, and a geometric mean (GM) of 105.2 Bq m^{-3} and 86 Bq m^{-3}, respectively. The arithmetic mean (AM) ($\pm$standard deviation SD) values are 148.4 ± 137.8 Bq m^{-3} and 160.6 ± 213.0 Bq m^{-3}, respectively. The AM, GM, and median values obtained in this work are comparable with those reported for other neighboring countries, such as Romania [2,48], Bulgaria [27], Macedonia [36], and Serbia [49]. The maximum values of radon concentrations in the Republic of Moldova are higher than the measured concentrations in Macedonia [36], Latvia [38], Poland [50], Hungary [26], Czech Republic [25], and Serbia [39,49], but lower than the published values in Bulgaria [4,27], Finland [28], Italy [31,35], Montenegro [37], and Austria [51].

The effective annual dose calculated with the aid of Equation (1), assuming an occupancy time of T = 1200 h for the children in a classroom (average 6 h per day, 20 working days per month, 10 months per year) ranges between the intervals 0.21–4.88 mSv y^{-1} (mean value 1.19 mSv y^{-1}) and 0.14–9.08 mSv y^{-1} (mean value 1.29 mSv y^{-1}) for the 2013–2014 and 2021 surveys, respectively. For the rooms characterized by high values of doses, supplementary remediation measures should be taken by the schools' managers and local authorities.

From the histogram drawn in Figure 4, based on the 2021 results presented for Chisinau region in Table A2—Appendix A, it can be noticed that the loglogistic distribution describes the radon concentration frequency distribution the best way. The lognormal distribution of radon data in schools was found in similar studies reported for various countries [26,27,31–33,50].

Through *cluster analysis*, the interaction within the relationship "*radon concentration x incidence/prevalence of diseases of the respiratory system, including bronchopulmonary cancer*" was established based on the results of this work and a national survey [47] (Table A2—Appendix A, Figure 5).

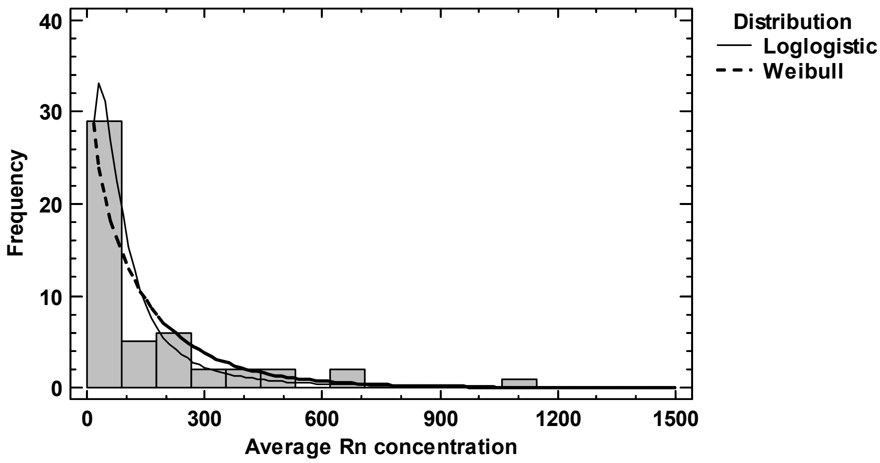


Figure 4. Frequency histogram of indoor radon concentrations (Bq m^{-3}) in the studied institutions in Chisinau region (2021, n = 49).

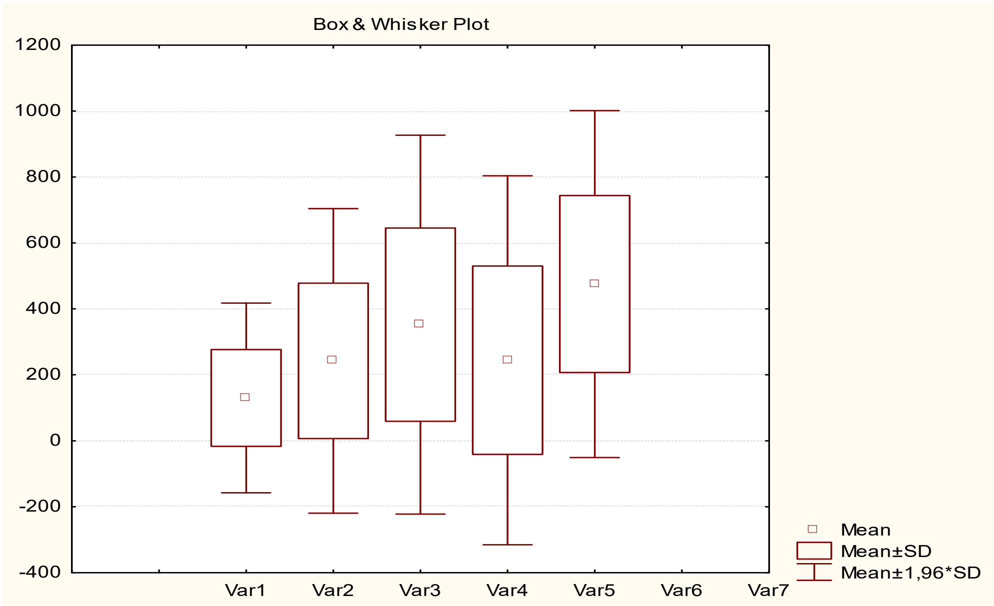


Figure 5. Distribution of radon concentrations in 2021 in schools from Chisinau region. Var 1—Kindergartens mun. Chisinau; Var 2—housing; Var 3—Underground galleries (Cricova and Mileștii Mici wine plants; Var 4—Cricova winery; Var 5—Mileștii Mici winery.

The 2021 study allowed us to identify the buildings where the radon concentration was higher than the international standards, especially in the kindergarten of Ialoveni rayon, village Nimoreni (355.73 Bq m^{-3}); Kindergarten nursery no. 30, mun. Chisinau, St. P. Zadnipru, 7/1 (492.24 Bq m^{-3}); Kindergarten nursery no. 130, mun. Chisinau, St. P. Zadnipru, 6/2 (464.67 Bq m^{-3}); Kindergarten nursery no. 149, mun. Chisinau, St. M. Drăgan, 6/1 (365.15 Bq m^{-3}); and Kindergarten nursery no. 211, mun. Chisinau, St. I. Vieru, 3 (657.94 Bq m^{-3}). All the indicated organizations are located in the Ciocana sector and are characterized by specific geological characteristics—such as the soil being represented by sandy chernozems. Increased concentrations of radon were also detected in two kindergartens in the Ialoveni district, wherein the buildings were characterized by the lack of basements: the theoretical high school, village Mileştii Mici, Ialoveni rayon (635.04 Bq m^{-3}) and gymnasium, Malcoci village, Ialoveni rayon (1129.25 Bq m^{-3}).

Geologically, most of the territory is located on the Middle and Upper Sarmatian rocks containing limestone, marl, clay, and sands, which are not hazards for radon; however, the thick distribution of gneiss and granite rocks from the oldest Archaic era can serve as a source of natural radon, especially given the porosity of the overlying rocks.

For the buildings with increased radon concentrations, the following measures have been proposed: to develop a dynamic radon concentration monitoring plan, which includes the intensification of ventilation; installation of modern ventilation systems; sealing cracks in walls and ceilings; and performing repeated control after measures are taken. At the same time, regular medical control of the staff is proposed, with special attention to the respiratory system. Risk awareness of exposure to radon was developed for parents and permanent staff. It would be useful for the decision-makers to take into account the mentioned risks, including measuring the radon concentration when the buildings are put into operation, and the sanitary authorities should consider including exposure to radon in the list of controls.

3.2. Influence of Abiotic Environmental Factors on the Concentration of Radon and Profile Plots from Complete Linkage Clustering

In order to establish the impact of abiotic environmental factors (temperature, humidity, etc.) on the distribution of radon concentrations, a clustered multifactorial analysis was performed with the determination of the Euclidean distance and the linkage distance of the interaction of the studied parameters. The formation of higher cluster A was demonstrated (Figure 6), comprising the parameters: radon concentration, maximum soil temperature adjacent to the building, average humidity, and minimum air humidity, which points out the significant influence of the nominated environmental factors on radon concentration.

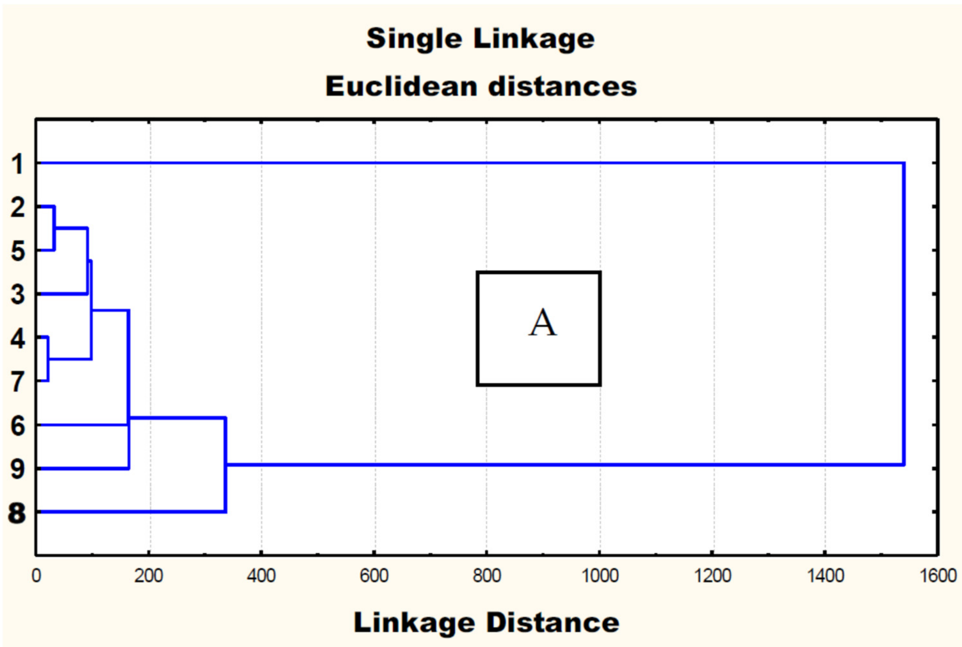


Figure 6. Cluster analysis of the influence of abiotic environmental factors (temperature and humidity of air and soil) on the concentration of radon in indoor air for 2021 campaign. 1—concentration ^{222}Rn, 2—average air temperature, 3—maximum air temperature, 4—minimum air temperature, 5—average soil temperature, 6—maximum soil temperature, 7—minimum soil temperature, 8—average air humidity, 9—minimum air humidity.

The Euclidean distance for the given cluster was 1580, which demonstrates the close connection between the components of the cluster. At the same time, it has been shown that the average air temperature, the maximum air temperature, the minimum air temperature, the average temperature of the soil, and the minimum temperature of the soil have a minor role in the exhalation of radon from the soil (Figure 6).

3.3. *Influence of Indoor and Outdoor Meteorological Parameters on Radon Concentrations in Educational Institutions from Chisinau Municipality and Ialoveni Rayon (2021, n = 49)*

In order to find a statistical relationship between radon concentrations in the studied kindergartens and temperature and humidity conditions in the indoor environment, as well as the outdoor environment [52,53], regression analyses were carried out with the support of the Statgraphics Centurion XVIII program. The results of a simple linear regression are shown in Table 3, which indicates that with an increase of 1 Celsius degree, the Rn concentration will decrease by 21.7 Bq m^{-3}.

Table 3. Correlation parameters of regression of radon concentration with indoor and outdoor meteorological conditions.

Correlation (Linear Simple Regression)	Correlation Coefficient	*p*-Value *	R-Squared, % **	Slope (Regression Coefficient)
Rn concentration—Indoor air temperature	−0.35	0.0128	12.5	−21.7
Rn concentration—Indoor air humidity	−0.02	0.9144	0.02	−0.3
Rn concentration—Outdoor air temperature	−0.41	0.0033	16.9	−12.4
Rn concentration—Outdoor air humidity	−0.14	0.3517	1.8	−6.2

* If *p*-value is less than 0.05 there is a statistically significant relationship at the 95.0% confidence level; ** The R-Squared statistic indicates that the model as fitted explains % of the variability of depended variable (Rn concentration).

A one-way regression analysis of the dependence of radon concentrations on indoor and outdoor meteorological factors showed that a statistically significant relationship was established for indoor and outdoor air temperatures (shaded cells), according to the *p*-value. However, the correlation coefficients show a relatively weak inverse relationship between the variables, as well as the trend reported by [52]. The minus sign indicates that as the parameter increases, the radon concentration decreases. The highest correlation coefficient (−0.41) is for the outdoor air temperature, and only 16.9% (R-squared) of the radon concentration variability in the kindergarten is explained by the outdoor air temperature (Figure 7).

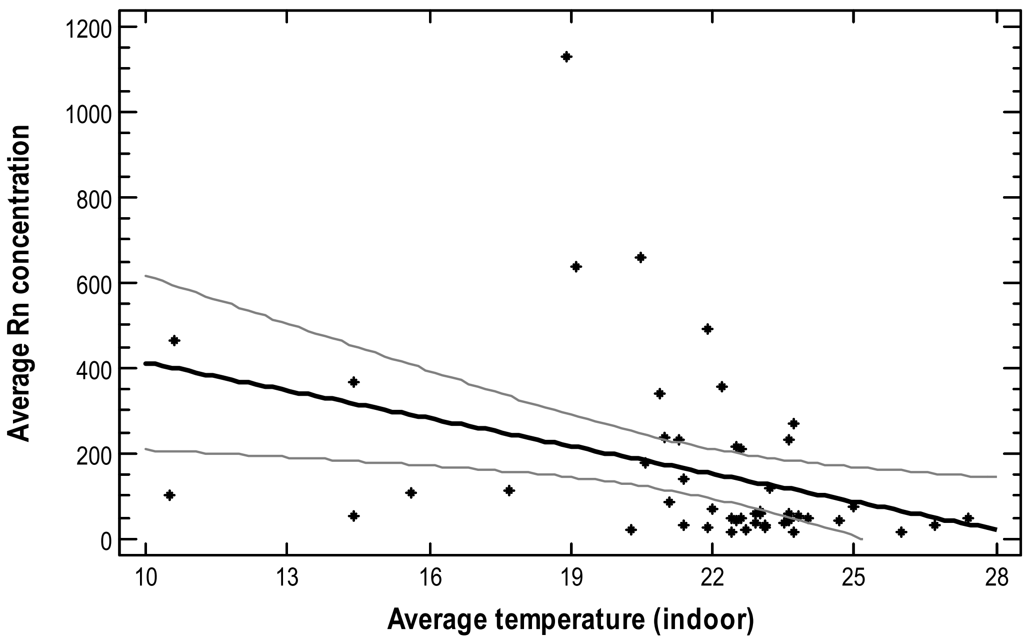


Figure 7. Plot of the fitted model of simple regression of radon concentration on indoor air temperature: Y axis—average radon concentration in institution (Bq m^{-3}); X axis—average air indoor temperature (Celsius degrees); points—observations; bold line—regression line; thin lines—95% confidence level area.

In turn, the variability of indoor air temperature could explain 12.5% of the Rn concentration on the premises. The slope (regression coefficient) shows the value at which the Rn concentration will change, independent of the change of variable; given this, the indoor temperature multiple regression analysis of the radon concentrations on all meteorological factors (indoor and outdoor) showed the presence of a stronger relationship with the highest statistical significance (Table 4).

Table 4. Multiple regression parameters of radon concentration on all meteorological factors.

Parameter	Slope (Regression Coefficient)	Standard Error	*p*-Value	R-Squared, %	Correlation Coefficient
CONSTANT	−846.263	364.714	0.0250		
Average temperature (indoor)	25.1631	9.44359	0.0107		
Average humidity (indoor)	24.5632	3.84542	0.0000		
Average temperature (outdoor)	−56.2977	7.84259	0.0000		
Average humidity (outdoor)	0.81462	5.71491	0.8873		
Multiple Regression in a whole		141.115	0.0000	59.76	0.77

The equation of the fitted multiple linear regression model describing the relationship between the average Rn concentration and four independent variables is the following:

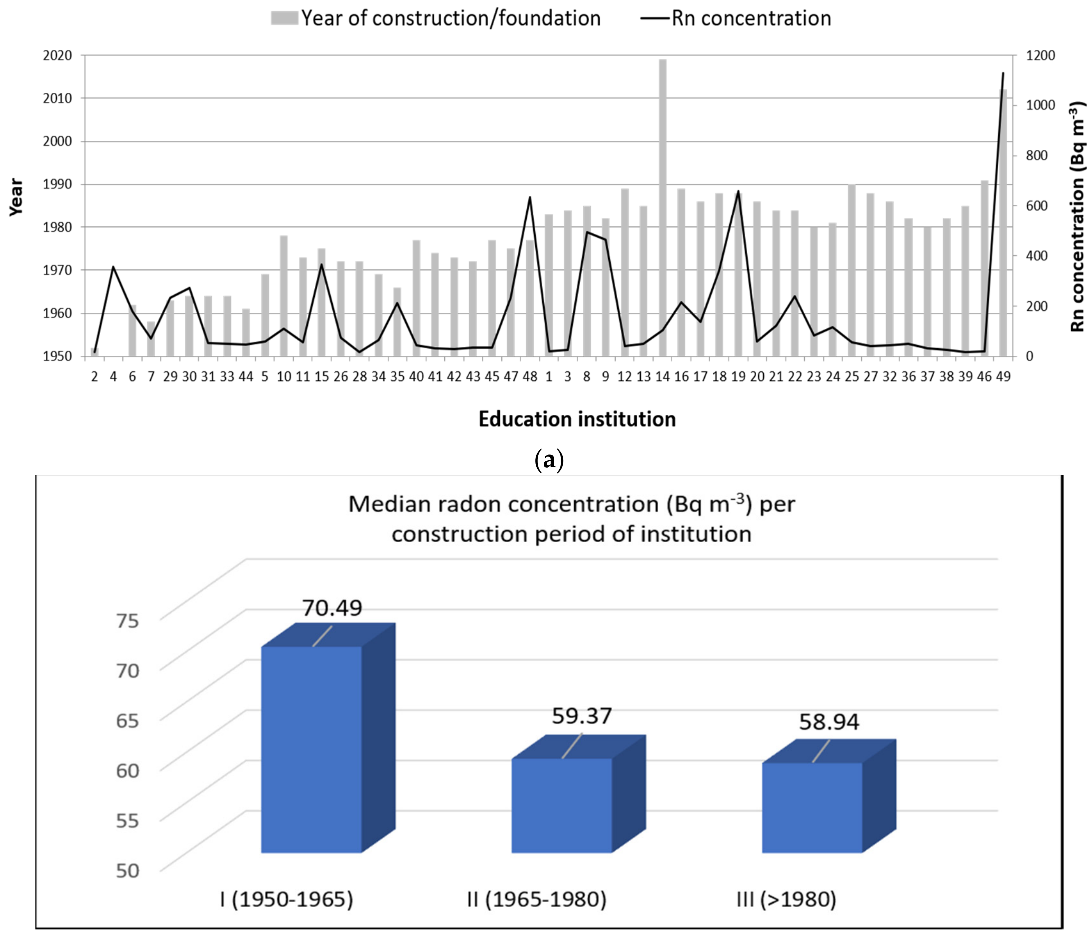
$$\textit{Average Rn concentration} = -846.263 + 25.1631 \times \textit{Average temperature (indoor)} + 24.5632 \times \textit{Average humidity (indoor)} - 56.2977 \times \textit{Average temperature (outdoor)} + 0.81462 \times \textit{Average humidity (outdoor)} \quad (2)$$

The standard error of the estimate shows the standard deviation of the residuals to be 141.115. This value can be used to construct prediction limits for new observations. Since the *p*-value of the model is less than 0.05 (0.0000), there is a statistically significant relationship between the variables at the 95.0% confidence level. The R-squared statistic indicates that the model as fitted explains 60% of the variability in Average Rn concentration and the correlation coefficient is 0.77 (high relationship).

Thus, a direct statistically significant relationship has been established between the radon concentration in buildings and the air temperature (indoor and outdoor); however, a stronger dependence of the radon concentration on external factors is manifested when all these factors are combined, including air humidity, which makes it possible to quantify fluctuations in the radon concentration with the variability of these factors.

3.4. Influence of Year of Building Construction on Radon Concentrations in Educational Institutions from Chisinau Municipality and Ialoveni Rayon (2021, n = 49)

According to the year of construction/foundation, educational institutions can be divided into three categories: (I) 1950–1965 ("minimalism of Khrushchev"); (II) 1965–1980, a larger standard of square meters per child; and (III) 1980–2020, more spacious buildings that are typical of nurseries/kindergartens. The share of the studied buildings from the first period is 18%, and the share from the second buildings is 31%, while the share from the third period is 51%, respectively. Despite the fact that the buildings of educational institutions were built several decades ago, there is no direct dependence between the radon concentration and the year of construction. Nevertheless, the dependence of the measured radon concentration on the construction year of the building, illustrated in Figure 8a, points out a decrease in the concentration, for the most part, in new buildings—with the exception of several institutions in Ialoveni rayon, including high schools. From Figure 8b, the results show that the median value of radon concentrations is higher for the old buildings (first category) compared to the buildings from age groups (II) and (III), a fact which might be related to the type of materials and techniques used during construction in each period [26,29,33,54].



(**a**)

(**b**)

Figure 8. (**a**) Plot of the radon concentration on year of construction (n = 49 institutions); (**b**) Plot of the variation of the median radon concentration with the age of construction.

4. Conclusions

1. During the periods of 2013–2014 and 2021, 149 radon investigations were carried out in educational institutions located in selected districts from the central and southern parts of the Republic of Moldova and 23,805 investigations were conducted in the Chisinau region, respectively, by using active/passive detectors RTM-1642 and RadonEye^{+2}, thereby establishing the minimum, average, and maximum values of the index in question. The results show an essential variability for the radio-stressogenic factor studied, depending on the geological conditions of the location of the building, age of the building, room floor level, and occupancy pattern.
2. During the preliminary research in 2013–2014, it was proved that in the air of the high school education institutions, the minimum concentration of radon, detected with the aid of active detectors, RTM-1642, was 26 Bq m^{-3}, and the maximum concentration was 427 Bq m^{-3}; moreover, in the early education institutions, the indices studied varied within the limits of 48 Bq m^{-3} and 607 Bq m^{-3}. The average value for the studied premises was 150.1 Bq m^{-3} and 147.1 Bq m^{-3}, respectively.
3. By using RadonEye^{+2} passive detectors, the results denote a variability in radon concentrations of 17.4–657.9 Bq m^{-3}, which were obtained in 2021 for early education institutions—with the average value being 127.6 Bq m^{-3}. For secondary/high school education institutions, the results indicate a concentration between 231.8–1129.3 Bq m^{-3}—with the average value being 665.4 Bq m^{-3}. Taking into account that most of the buildings investigated were of an older age, we can admit that the detected values of

the radon concentration were within the national norms, which are stipulated in the normative acts.

4. By comparing the results obtained in this work with the concentration of radon reported at the national level in 2021 in the air of dwellings, where the indicator varied in the range of 51.55–728.38 Bq m^{-3}—and with an average value of 242.37 Bq m^{-3}—it was proved that in educational institutions the index was lower, which is a fact that is explained by the use of additional fans on the mentioned premises.
5. Based on the investigation of radon concentrations in the indoor air of educational institutions located in the territory of the Republic of Moldova and the associated annual effective dose for the population of school-aged children, the basis of data reflecting the radioactivity that the population of the Republic of Moldova is exposed to was updated, including children's exposure to natural sources of ionizing radiation. For the locations displaying high radon concentrations, which exceed the international/national standards, safety measures should be adopted in order to protect the children's health.
6. New data have been obtained in order to sustain the argument for updating the national reference levels of radon in dwellings (300 Bq m^{-3}) in the context of Euratom Directive no.2013/59/.
7. Based on the cluster analysis, with the evidence of the Euclidean and linkage distances, it was established that the concentration of radon in the indoor air was in close dependence with exogenous factors (soil temperature/air humidity), the type of building materials, the type of soil/rocks adjacent to the constructions, the sealed foundation, and the ventilation in the rooms.

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

Appendix A

Table A1. The average concentration of radon (Bq m^{-3}) and relative error (%) indicated by the instrument in the indoor air of early education institutions and primary, gymnasium and high school education institutions on the territory of the Republic of Moldova (period 2013–2014, warm time of year) (n = 29 buildings/N = 149 measurements; working regime of the radonometer: 30 min).

No.	Date	Rayon (R)/Locality	Institution, Type of Dwelling, Building Description	Average Radon Concentration, Bq m^{-3}, and Relative Error	Pressure, mm Hg	Temperature, °C	Humidity, %	N
1.	6 August 2013	R. Ungheni	Early education institution "Guguţă", game room, 1st floor	96 ± 26%	997	26.5	55	3
2.	6 August 2013	R. Ungheni	Theoretical high school, study room, 1st floor	48 ± 35%	1010	29.5	50	3
3.	6 August 2013	R. Ungheni	Theoretical high school, study room, 2nd floor	26 ± 52%	1010	29.0	59	3
4.	20 May 2014	R. Căuşeni	Early education institution No. 7 with 2 floors, closet, 1st floor	78 ± 28%	1016	22.5	65	7
5.	23 May 2014	R. Leova, village Sărăţica Nouă	Gymnasium food warehouse, 1st floor, old type construction	210 ± 17%	1004	23.0	66	6
6.	23 May 2014	R. Leova, village Sărăţica Nouă	Early Education Institution, 1st floor, old type adobe house, kitchen	132 ± 21%	1003	22	78	5
7.	26 May 2014	R. Criuleni	Early education institution "Birch", Donici, St. old type construction made of adobe	196 ± 18%	1009	26.0	65	6
8.	27 May 2014	R. Ialoveni	Theoretical high school, 1 Basarabia St., dishwasher room, 1st floor	36 ± 47%	1001	25.5	77	6
9.	27 May 2014	R. Ialoveni	Early education institution No. 5, 1 Basarabia St., warehouse, 1st floor	60 ± 32%	999	23.0	70	6
10.	16 June 2014	R. Ialoveni, village Zâmbreni	Early education institution, warehouse no. 2, ground floor	108 ± 24%	1008	23.5	64	6
11.	16 June 2014	R. Ialoveni, village Zâmbreni	Theoretical high school, ground floor	42 ± 38%	1003	25.0	57	4
12.	17 June 2014	R. Ialoveni, village Horaşti	Early education institution Nursery, ground floor, warehouse	92 ± 27%	1008	22	73	4
13.	17 June 2014	R. Ialoveni, village Horaşti	Theoretical high school, technological education cabinet, basement	427 ± 12%	1007	23.0	69	6
14.	18 June 2014	R. Ialoveni, village Mileştii mici	Early education institution Nursery, kitchen area, warehouse	174 ± 20%	1001	21	69	5
15.	18 June 2014	R. Ialoveni, village Mileştii mici	Theoretical high school, the kitchen area	385 ± 7%	1001	20.0	76	3
16.	19 June 2014	R. Ialoveni, village Malcoci	Gymnasium, locker room	365 ± 13%	996	22.5	62	6

Table A1. *Cont.*

No.	Date	Rayon (R)/Locality	Institution, Type of Dwelling, Building Description	Average Radon Concentration, Bq m^{-3}, and Relative Error	Pressure, mm Hg	Temperature, °C	Humidity, %	N
17.	20 June 2014	R. Ialoveni, village Nimoreni	Early education institution, warehouse, ground floor	607 ± 10%	994	23	63	7
18.	20 June 2014	R. Ialoveni, village Nimoreni	Institution of early education, warehouse, basement	115 ± 35%	994	21.5	71	5
19.	1 July 2014	R. Hancesti	Early education institution no. 6, 6 Veronica Micle St., ground floor, bedroom.	192 ± 18%	996	26.5	48	6
20.	1 July 2014	R. Hancesti	Theoretical high school M. Eminescu, 43 Eminescu St., primary class, study room, 1st floor	47 ± 36%	997	24.5	69	6
21.	2 July 2014	R. Hancesti	Fundul Galbenei Gymnasium	29 ± 46%	1001	23	67	5
22.	2 July 2014	R. Hancesti	The institution of early education Albinuţa, bedroom, ground floor	174 ± 19%	996	21.5	80	5
23.	3 July 2014	R. Hancesti, village Buţeni	The early education institution of Romanita, the cellar, basement	173 ± 19%	1001	22	70	5
24.	3 July 2014	R. Hancesti	Anton Bunduchi Gymnasium, 20 Renasterii St.	164 ± 19%	998	22	62	5
25.	4 July 2014	R. Hânceşti, village Logăneşti	Early childhood education institution, bedroom	60 ± 32%	1004	20	73	6
26.	4 July 2014	R. Hânceşti, village Logăneşti	Gymnasium Logăneşti	92 ± 27%	1004	21.5	75	4
27.	13 August 2014	R. Hancesti, village Mereşeni	Gymnasium Mereşeni, kitchen, ground floor	80 ± 29%	998	28	59	5
28.	13 August 2014	R. Hancesti, village Mereşeni	Mereşeni early education institution, bedroom, 2nd floor	48 ± 35%	994	28.5	60	5
29.	21 August 2014	Comrat town	Early Education Institution no. 4, 38 Puşkin St.	48 ± 35%	1004	28	58	6
	Total *n* = 29 buildings					Total N = 149		

Table A2. The buildings characteristics, abiotic factors and mean value of the radon concentration measured in 2021 survey with RadonEye+[2] detectors in education institutions in Chisinau municipality and Ialoveni rayon, Republic of Moldova (*n* = 49 buildings/N = 23805 measurements; working regime of the device: hourly; measurement uncertainty:<10%).

No.	Period	Institution and Address	Year of Construction	Average Radon Concentration (Bq m^{-3})	N	Average Temperature, °C (Indoor)	Average Humidity, % (Indoor)	Average Temperature, °C (Outdoor)	Average Humidity, % (Outdoor)
1.	23 February 2021–19 March 2021	Kindergarten nursery no. 175, mun. Chisinau, St. Grenoble, 153/1	1983	20	573	22.7	24	4.3	72.2

Table A2. *Cont.*

No.	Period	Institution and Address	Year of Construction	Average Radon Concentration (Bq m^{-3})	N	Average Temperature, °C (Indoor)	Average Humidity, % (Indoor)	Average Temperature, °C (Outdoor)	Average Humidity, % (Outdoor)
2.	23 February 2021–17 March 2021	Kindergarten nursery no. 12, mun. Chişinău, St. M. Eminescu, 62	1952	17.78	531	22.4	21	4.4	71.3
3	23 February 2021–19 March 2021	Kindergarten nursery no. 174, mun. Chisinau, St. Vl. Corolenco, 59A	1984	25.43	552	21.9	25	4.3	72.2
4	25 February 2021–19 March 2021	Kindergarten Ialoveni rayon, village Nimoreni	1950	355.73	548	22.2	38	4.9	70.3
5	1–22 April 2021	Kindergarten nursery no. 1, mun. Chisinau, Bubuieci commune, St. Livezilor, 29/4	1969	59.37	497	23.6	26	7.8	62.4
6	1–22 April 2021	Kindergarten nursery no. 128, mun. Chisinau, St. Otovasca, 21	1962	178.38	498	20.6	37	7.8	62.4
7	2–23 April 2021	Kindergarten nursery no. 67, mun. Chisinau, St. Otovasca, 11	1958	70.49	479	22	37	7.8	62.4
8	1–22 April 2021	Kindergarten nursery no. 30, mun. Chisinau, St. P. Zadnipru, 7/1	1985	492.24	500	21.9	40	7.8	62.4
9	1–22 April 2021	Kindergarten nursery no. 130, mun. Chisinau, St. P. Zadnipru, 6/2	1982	464.67	497	10.6	44	7.8	62.4
10	1–22 April 2021	Kindergarten nursery no. 135, mun. Chisinau, St. M. Sadoveanu, 6/2	1978	109.45	502	15.6	51	7.8	62.4
11	1–22 April 2021	Kindergarten nursery no. 138, mun. Chisinau, St. M. Drăgan, 6/1	1973	55.22	501	14.4	42	7.8	62.4
12	1–23 April 2021	Kindergarten nursery no. 225, mun. Chisinau, bd. Mircea cel Batran, 14/2	1989	40.41	521	22.5	24	7.9	62.9
13	1–22 April 2021	Kindergarten nursery no. 2, mun. Chisinau, Bubuieci commune, Stefan cel Mare St., 29/3	1985	49.45	496	22.6	29	7.8	62.4
14	1–22 April 2021	Kindergarten nursery no. 155, mun. Chişinău, St. I. Vieru, 5/1	Re-opened 2019	103.85	501	10.5	53	7.8	62.4
15	1–22 April 2021	Kindergarten nursery no. 149, mun. Chisinau, St. M. Sadoveanu, 4/4	1975	365.15	501	14.4	46	7.8	62.4
16	1–23 April 2021	Kindergarten nursery no. 212, mun. Chisinau, 3/1 N.M. Spatarul St.	1989	214.63	520	22.5	39	7.9	62.9
17	1–22 April 2021	Kindergarten nursery no. 188, mun. Chişinău, St. I. Vieru, 8/2	1986	137.7	501	21.4	31	7.8	62.4
18	1–23 April 2021	Kindergarten nursery no. 197, mun. Chisinau, bd. Mircea cel Batran, 4/2	1988	341.79	522	20.9	37	7.9	62.9

Table A2. *Cont.*

No.	Period	Institution and Address	Year of Construction	Average Radon Concentration (Bq m^{-3})	N	Average Temperature, °C (Indoor)	Average Humidity, % (Indoor)	Average Temperature, °C (Outdoor)	Average Humidity, % (Outdoor)
19	1–22 April 2021	Kindergarten nursery no. 211, mun. Chisinau, St. I. Vieru, 3	1988	657.94	433	20.5	46	7.8	62.4
20	1–22 April 2021	Kindergarten nursery no. 184, mun. Chisinau, St. P. Zadnipru, 3/1	1986	58.94	497	23	31	7.8	62.4
21	1–22 April 2021	Kindergarten nursery no. 177, mun. Chisinau, St. Volunteers, 14/3	1984	121.23	500	23.2	38	7.8	62.4
22	1–22 April 2021	Kindergarten nursery no. 179, mun. Chişinău, St. M. Sadoveanu, 1	1984	238.68	503	21	41	7.8	62.4
23	1–22 April 2021	Kindergarten nursery no. 161, mun. Chisinau, St. A. Russo, 61/3	1980	83.89	504	21.1	36	7.8	62.4
24	1–22 April 2021	Kindergarten nursery no. 32, mun. Chisinau, St. M. Sadoveanu, 2/2	1981	115.86	502	17.7	41	7.8	62.4
25	9–30 June 2021	Nursery-kindergarten no. 216, mun. Chisinau, bd. Decebal, 82/3	1990	56.54	498	22.9	58	21.2	72.2
26	8–30 June 2021	Kindergarten nursery no.71, mun. Chisinau, bd. Dacia, 28/2	1972	75.1	528	25	57	21.1	72
27	9–29 June 2021	Nursery kindergarten no. 49, mun. Chisinau, St. Independentei, 32/2	1988	42.14	475	23.6	59	21	72.5
28	8–29 June 2021	Nursery-kindergarten no. 17, mun. Chisinau, St. Zelinsky, 33/3	1972	17.53	501	26	53	20.9	72.3
29	8–29 June 2021	Nursery-kindergarten no. 77, mun. Chisinau, St. Zelinsky, 32/7	1963	232.73	501	23.6	62	20.9	72.3
30	8–29 June 2021	Nursery-kindergarten no. 89, mun. Chisinau, St. Zelinsky, 26/3	1964	270.74	501	23.7	59	20.9	72.3
31	9–29 June 2021	Nursery-kindergarten no. 91, mun. Chisinau, St. Zelinsky, 36/5	1964	52.21	479	23.8	53	21	72.5
32	8–30 June 2021	Nursery-kindergarten no. 182, mun. Chisinau, St. Cuza Vodă, 39/3	1986	43.91	525	23.6	55	21.1	72
33	23–29 June 2021	Nursery-kindergarten no. 79, mun. Chisinau, St. Zelinsky, 28/7	1964	50.91	143	27.4	58	24.7	65.1
34	8–29 June 2021	Nursery-kindergarten no. 106, mun. Chisinau, St. Hristo Botev, 19/4	1969	65.18	502	23	59	20.9	72.3
35	9–29 June 2021	Nursery-kindergarten no. 96, mun. Chisinau, St. N. Zelinski, 12/2	1966	212.42	476	22.6	63	21	72.5
36	8–30 June 2021	Nursery-kindergarten no. 40, mun. Chisinau, Bd. Dacia, 24/2	1982	49.49	520	22.4	65	21.1	72

Table A2. *Cont.*

No.	Period	Institution and Address	Year of Construction	Average Radon Concentration (Bq m^{-3})	N	Average Temperature, °C (Indoor)	Average Humidity, % (Indoor)	Average Temperature, °C (Outdoor)	Average Humidity, % (Outdoor)
37	8–30 June 2021	Nursery-kindergarten no. 165, mun. Chisinau, St. Cuza Vodă, 7/5	1980	32.35	525	26.7	54	21.1	72
38	8–30 June 2021	Nursery-kindergarten no. 168, mun. Chişinău, St. Cuza Vodă, 29/7	1982	25.6	524	23.1	59	21.1	72
39	9–30 June 2021	Nursery-kindergarten no. 180, mun. Chisinau, bd. Dacia, 53/3	1985	17.37	497	23.7	58	21.2	72.2
40	8–30 June 2021	Nursery-kindergarten no. 153, mun. Chisinau, bd. Dacia, 36/2	1977	45.29	510	24.7	59	21.1	72
41	9–29 June 2021	Nursery-kindergarten no. 142, mun. Chisinau, bd. Trajan, 17/2	1974	32.48	477	23.1	64	21	72.5
42	9–30 June 2021	Nursery-kindergarten no. 151, mun. Chisinau, St. Grenoble, 207	1973	30.38	500	21.4	66	21.2	72.2
43	9–29 June 2021	Nursery-kindergarten no. 122, mun. Chisinau, St. Independentei, 9/3	1972	35.97	478	23.5	62	21	72.5
44	17 August 2021–7 September 2021	Nursery-kindergarten no. 78, mun. Chisinau, St. Gh. Asachi, 35	1961	47.82	518	24	55	17.7	63.9
45	17 August 2021–7 September 2021	Nursery-kindergarten no. 8, mun. Chisinau, St. Gh. Asachi, 64/2	1977	36.65	503	22.9	51	17.7	63.9
46	17 August 2021–7 September 2021	Nursery-kindergarten no. 227, mun. Chisinau, St. V. Dokuchaiev, 3/1	1991	20.74	439	20.3	53	17.7	63.9
47	25 February 2021–19 March 2021	Theoretical high school, village Horăşti, Ialoveni rayon	1975	231.8	47	21.3	31	4.9	70.3
48	25 February 2021–19 March 2021	Theoretical high school, village Mileştii Mici, Ialoveni rayon	1977	635.04	479	19.1	49	4.9	70.3
49	25 February 2021–19 March 2021	Gymnasium, Malcoci village, Ialoveni rayon	2012	1129.25	480	18.9	54	4.9	70.3

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