Heliyon 5 (2019) e01737

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.heliyon.com

Review Article

Radon interventions around the globe: A systematic review

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ARTICLE INFO

Keywords:
Environmental Science

ABSTRACT

Background: Radon is the primary source of environmental radiation exposure posing a significant human health risk in cold countries. In Canada, most provinces have revised building codes by 2017, requiring construction solutions to avoid radon in all new buildings. While various construction solutions and remediation techniques have been proposed and evaluated, the question about the best method that would effectively reduce radon in a variety of contexts remained unanswered. Radon practitioners, officials of radon control programs, and businesses offering radon testing and mitigation services, builders, property managers, homeowners and residents also have similar queries.

Objective: This paper systematically reviewed both experimental and observational studies (S) with radon interventions (I) used globally in residential houses (P) compared to other residential or model houses (C) to evaluate relative mitigation effectiveness (O) that could guide selecting the best radon reduction strategy for residential buildings.

Methods: Two researchers searched fifteen academic bibliographic and grey literature databases for radon intervention studies conducted around the world, with particular emphasis on areas of North America and Europe published from 1990 to 2018.

Interventions in residential and model houses were included, but studies piloted purely in the lab were excluded; the PRISMA checklist was used to synthesize data; Cochrane and Hamilton tools were used to evaluate study quality.

Results: Studies around the globe have investigated a variety of construction solutions, radon mitigation and remediation systems with different levels of effectiveness. In most cases, sub-slab or sump depressurization system (SSDS) with active ventilation technique was found more effective in achieving a significant and sustained radon reduction than the passive methods such as sealing, membrane, block and beam, simple ventilation, or filtration. The choice of an optimal strategy largely depends on the factors related to the initial radon level, routes of entry, building design and age, as well as other geologic, atmospheric, and climatic conditions.

Conclusion: Although an active SSDS is the best mitigation systems, at places, it needs to be combined with another system and installed by a trained radon professional considering the pertinent factors to ensure radon level continues to remain below the action level. This study did not conduct any economic evaluation of the mitigation measures. Future review with studies on the implementation of new building codes will provide updated evidence.

Recommendation: For the practical implementation of radon mitigation, training of the construction industry, information provision for residents, the establishment of public funds, incorporation of radon-prone areas in the land utilization maps, and enacting building codes deemed essential.

1. Introduction

Radon (Rn^{222}) gas is a product from the decay chain of uranium (U^{238}), originates from Ra^{226} (Radium) and enters buildings mainly through the porous basement foundations (WHO, 2009). Both the World Health Organization (WHO, 2009) and the International Agency for Research on Cancer (ICRP, 2007) identified radon as a category one human carcinogen. The universal outdoor radon concentration is

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https://doi.org/10.1016/j.heliyon.2019.e01737
Received 9 April 2019; Received in revised form 6 May 2019; Accepted 13 May 2019

between 5 and 15 Bq/m^3, and it does not pose any health risk (WHO, 2016). However, the short-lived radon progenies (P^{218}, Pb^{214}, Bi^{214}, and P^{214}) can accumulate in closed spaces (caves, mines, indoors) and emit radioactive alpha particles that upon inhalation remain in the lung tissues and mutate DNA to cause cancer (Gustavino et al. 2014; ICRP, 2007).

Although the health effect of radon has been known for over half a century and it has been responsible for about 15% lung cancer deaths globally (WHO, 2009), until recently a few countries have taken constitutional action to address the threat. As per the International Residential Code (2010), an effective radon control method should be in place during all new constructions, particularly in areas where radon level is frequently found high. The Council of the European Union (2013) enacted the *Basic Safety Standards Directive* in 2013 that requires member states to address the radon issue by developing action plans. Many European countries and most states of the USA have adopted buildings codes conforming to the international standards (National Conference of State Legislatures, 2015).

Canadian federal government has a model national building code that provides broad policy direction with no legal status (National Research Council Canada, 2017). However, it becomes an act once accepted by the provincial and territorial governments (Canadian Environmental Law Association, 2017). Most provinces and territories (except Ontario and Quebec) of Canada revised the building codes by 2017 where builders require construction solutions to avoid indoor radon in all new dwellings (CELA, 2017).

Despite these updated building codes and free, accessible handbooks and guidelines, homeowners of existing houses in most countries do not require to test, mitigate (to reduce the exposure in existing homes by applying various temporary methods) and remediate (to install a systematic technique to sustainably reduce exposure to radon below the reference level) radon. They do not also need to declare the radon status of properties during the real-estate transactions. Consequently, recent studies in Alberta found an average of 31.5% higher radon level in the new houses compared to the existing ones built before 1992 (Stanley et al., 2017). Thus, many informed citizens enquired about the best mitigation system and the optimal time to test and install that. Radon practitioners, officials of radon control programs, and businesses offering radon testing and mitigation services, builders, property managers, homeowners and residents also have similar queries regarding the implementation of building codes for different types of houses and geographical locations. Studies around the world have been evaluating the effectiveness of active (that uses an electric fan), passive (gets benefit only from natural ventilation) as well as other mitigation techniques in combination for decades. However, the question about the best mitigation system that would work in a variety of contexts remained unanswered. By the best method, we meant the one that can effectively and sustainably reduce radon below the reference level; it is also cost-effective, less disruptive to install, feasible for the majority of dwellings, and easy to maintain. In this review, we mainly focused on the overall effectiveness of the radon control systems.

We conducted a systematic review of both experimental and observational studies (S) with radon mitigation interventions (I) in residential houses (P) of countries around the world, with a focus on areas of North America and Europe that have cold climates and similar construction practices to Canada. The interventions were compared to the ones installed or conducted in the residential or model houses (C) to evaluate the relative radon reduction effectiveness (O) that could guide selecting the best mitigation strategy for residential buildings in Canada and beyond.

The objective of the present review was to answer three research questions:

a) What is (are) the most effective radon control system (s) in terms of reducing radon below the action level in both new and existing houses?
b) What is the best timeline to test and install the control system(s) in the new and existing residential houses?
c) What factors are worthy of consideration while planning for controlling radon in a house?

2. Methods

2.1. Protocol and registration

A systematic review protocol was developed and registered with the National Institution of Health Research, UK. The registration number and link: CRD42018110016.

2.2. Eligibility criteria

This review of evidence on the effectiveness of radon interventions did not involve human subjects. We selected both experimental and observational studies with radon interventions. Geographically, we included studies mainly from Europe and North America but also considered suitable studies conducted in other cold countries. We included only the residential and experimental model houses but excluded studies reporting only indirect experimental measures of effectiveness in pure laboratory settings. The selection of literature was limited to English language; medical and public health disciplines but excluded studies conducted under all other disciplines. The selection was not limited by the publication status and included studies conducted between 1990 and 2018.

2.3. Information sources

Fifteen academic bibliographic databases (Academic Search Complete, ACCESS Digital Library, Avery Index, CAB Abstracts, CINAHL, The Cochrane Library - OVID & Wiley, EMBASE, Erudite, Geobase, Global Health, IBSS, PubMed- Medline, PAIS, PsycINFO, Web of Science) and grey literature (government survey report, other data or systems' reports from the WHO, ICRP, EPA, EU etc.) were searched for radon intervention studies and related documents published from 1990 to 2018. Additionally, reference lists of the selected articles, textbooks were searched; radon researchers and experts were requested for any relevant documents. The last search was made in December 2018 to supplement the review with the most recent contents.

2.4. Search strategy

Two researchers independently searched electronic databases, screened and critically appraised studies following the search criteria using Medical Subject Headings (MeSH) with help from a librarian at the University of Ottawa. MeSH words included 'Radon,' 'Testing,' 'Retesting,' 'Intervention,' 'Mitigation,' 'Depressurization,' 'Sump,' 'Barrier,' 'Membrane,' 'Ventilation,' 'Air Cleaner,' 'Radon Well,' 'Effectiveness', 'Time,' 'Factor,' 'Geology,' 'Climatic,' 'Atmospheric,' in various combination of search. An example of the search strategy applied by Dr. James Gomes on Thu June 2, 2017, at 17:23:56 in PubMed was (((((radon) AND (intervention) OR (Remediation) OR (mitigation) OR (assessment) AND (Depressur*) OR (Sump) OR (Barrier) OR (Membrane) OR (Ventilation) OR (Air Cleaner) OR (Radon Well) AND (effectiveness) [ptyp])))))

PubMed Results.

Items 1–115 of 115 (Display the 115 citations in PubMed). The limits put were peer-reviewed articles and period of publication from 1990-2018.

2.5. Study selection

Sixty-six documents were included for the final review: 53 peer-reviewed articles and 13 other types of documents (Fig. 1 below). Among the 53 peer-reviewed articles, 15 were on radon remediation

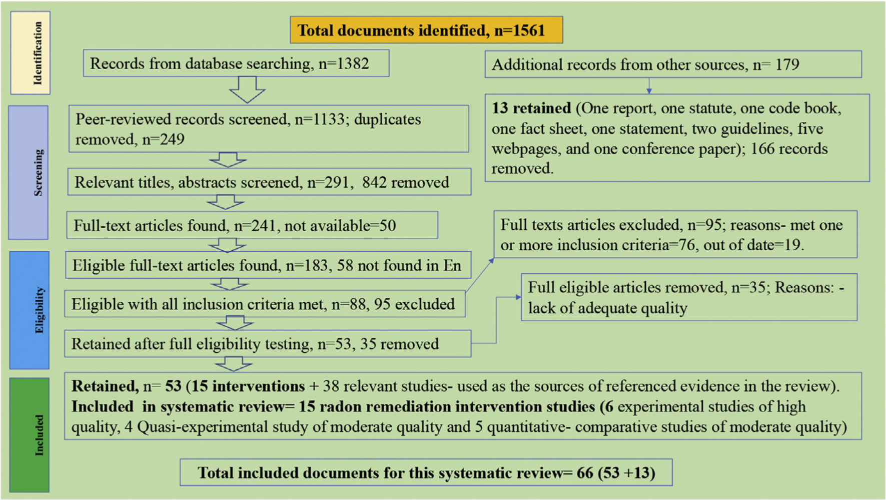

Fig. 1. PRISMA Flow Chart: Systematic review

interventions that were thoroughly reviewed (Table 1 below), and data extracted. Other 38 documents related to the factors that affect radon mitigation and relevant information. Among the 15 articles, six were experimental (high quality), four quasi-experimental (moderate quality), and five quantitative comparative studies (moderate quality). Among the 38 relevant articles, 11 were experimental (high quality), three reviews (high quality), and 18 quantitative studies (moderate quality). Besides, there was one case-control study, four case studies, and one qualitative study. All of these studies including the qualitative article were of high quality. As mentioned above, variations of measures made very little quantitative synthesis possible; thus, the synthesized data were not suitable for meta-analysis. The disparities remained even after grouping up the interventions and outcomes; so, the data were summarized narratively.

2.6. *Data collection process*

Two researchers extracted data independently but met regularly to discuss findings, compare the outcomes of search, and agree with consensus about the inclusion of documents in the review based on the review protocol developed earlier. Data were then, collated in a single spreadsheet. The PRISMA 2009 (Moher et al., 2009) checklist was followed to synthesize data. Quality of the experimental studies and uncontrolled studies was assessed by using the Cochrane risk of bias tool and Hamilton tool respectively. The criteria for quality at the study level was measured with the existence of a suitable comparison group and at the outcome level with the reliability and validity of the data for each important outcome by identifying the methods employed to assess them in each study (Moher et al., 2009).

2.7. *Data items*

The article-wise data were listed under sub-headings of background, objective, method, measures, intervention, outcomes, limitations, conclusion, recommendation and applicability. The outcomes were defined as effectiveness of the mitigation technique in terms of percent reduction of radon level after mitigation compared to the pre-mitigation level of radon in the intervention and control houses across the studies conducted in different countries. The assumption was that every mitigation technique would reduce radon level at a certain level that was simplified to express in percentage whatever unit of measurement a study might have used.

2.8. *Risk of bias in individual studies*

The study design was assessed to determine the risk of bias of individual studies and the reliability and validity of the data were evaluated for each important outcome by identifying the methods employed and analyses used to assess the outcomes. Both study and outcome level information was used in synthesis.

2.9. *Summary measures and synthesis of results*

As the effectiveness was presented in percentage without always mentioning the means and confidence intervals, the principal summary measures could not be estimated.

2.10. *Risk of bias within studies*

The intervention studies conducted from 1990 till 2018 were selected whereas most of the provinces/territories of Canada adopted or revised building codes by 2017, thus, there remained a publication bias that may affect the cumulative evidence. As the focus was on the effectiveness of radon mitigation, only the selected parts of study findings that dealt with this aspect leaving other findings. However, this has not affected the cumulative evidence on the effectiveness of radon remediation. Besides, there is a possibility that some studies, typically those with positive ('statistically significant') results, are more likely than others to be published and therefore included in a review.

2.11. *Risk of bias across studies*

After assessing the individual study, the bias across the studies was evaluated. The risks of bias included studies from publication, selection and reporting are described in the discussion section of the review.

2.12. *Additional analyses*

Other related factors that influence radon mitigation are narratively described. No further analyses such as sensitivity or subgroup analyses were conducted due to the lack of adequate numeric data. No meta-regression was also done due to lack of homogeneity of the study protocols, measures and outcomes across the selected studies.

Table 1

List of selected studies of radon mitigation intervention with relative effectiveness.

Study Design, Citation, location	Population, Sample, Measures, Duration of follow up/Timeline	Interventions, Comparison	Baseline Radon Before Mitigation (Bq/m^3)	Outcome After Mitigation (Bq/m^3)	Effectiveness* (*measured as the percentage of difference between pre- and post- remediation radon level)
Quantitative-comparative study by Stanley et al. (2017) in Calgary, Canada.	2382 residential homes tested for radon for at least 90 days (median 103 d) between 2013 and 2016. High radon level homes were remediated and retested to determine the efficacy of radon reduction techniques.	Sub-slab depressurization mainly but in a minority of cases, radon-impermeable membrane installed.	Average 126 (range >15–3441); 1135 homes had >=100; 295 homes had >= 200; 90 homes had average 575.	Mitigated 90 homes with av. 575 radon and noted reduced av. levels of 32.5. The house with the highest radon level of 3441 was reduced to 86	Highest mitigation efficacy recorded was 97.5%; Mitigation was effective in reducing radon levels to below 100 Bq/m^3 in all cases and typically reduced levels by 92%.
Experimental study by Boardman and Glass (2015) in Wisconsin, USA	A single-zone air infiltration model was calibrated to measure tracer gas, soil moisture, and air exchange rate.	Active soil or sub-slab depressurization system (AS/SSDS)	321.9 ± 5.18	11.1 ± 7.4	96.5% efficiency in radon reduction; >75% reduction in moisture
Quasi-experimental study by Brossard et al., (2015) in Canada.	Mitigated nine houses by installing SSDS with two types of discharge and fan locations: Basement or roof-discharge.	Sub-slab depressurization systems (SSDS) with fans at two levels	322–1931	Below <15 to 196	91+_6% at ground level and 94+_5% at the attic level
Quasi-experimental study by Brossard et al. (2015) in Quebec, Canada.	Above ground level (AGL) discharge with the fan located in the basement and above roof line (ARL) discharge with the fan located in the attic.	Sub-slab depressurization systems (SSDS)	Above 300	ARL (Avg%, SD) = 75.3 ± 13.6; and AGL = 74.3 ± 20.8	ARL 89%, AGL 95%.
Quantitative-comparative study by Groves-Kirkby et al. 2006 in Northamptonshire and neighbouring counties, UK.	After measuring radon levels, 73 post constructed houses remediated with fan-assisted sump pump and compared with 64 houses remediated during construction with protective radon membrane only.	Fan-assisted sump-pump and protective membrane used as damp-proof; included a cavity tray to seal the membrane together with weep-holes in it for drainage.	Post-construction houses: 516; During construction houses: 458	Post construction houses: 60; During construction houses: 107.	With active sump-pump 100% and with protective membrane only 89%
Quantitative-comparative study by Groves-Kirkby et al. (2008) in the UK	Radon concentration data collected from 170 homes situated in Radon Affected Areas in Northamptonshire and neighbouring counties.	Conventional sump-pump technology by a commercial organization	487.6	64.6	100% of remediated homes achieved reduction to below the Action Level of 200 Bq/m^3 and more than 75% of the sample exhibiting mitigation factors of 0.2 or better.
Experimental study by Marley and Phillips, 2001 in Northamptonshire, UK.	Studied four model single story buildings with construction design similar to local houses.	Air-Conditioning (AC) and Central Heating without AC	96–1083	Much lower than the UK action level of preceding level.	40–100%
Quantitative-comparative study by Long et al.,(2013 in three counties of Ireland.	Radon level tested in houses of North Cork (n = 152);South and West Cork (n = 105) counties.	Homes exceeding the reference level remediated with active sump technique.	North Cork: Max 3300; 126 houses >200; 26 houses >800. South and West Cork: Max 1000; 105 houses >200 and 3 houses >800	<200	92%
Quantitative-comparative study by Huber et al., 2001in western Tyrol, Austria,	Five years after mitigation, five different remedial actions were examined in five houses for their efficiency	House 1: A mechanical intake and outlet ventilation with heat exchanger combined with a SSDS. House 2: SSDS with two fans and loops of drainage tubes to withdraw radon from the area below the floor. House 3: A multilayer floor construction, with a fan to suck radon from a layer between bottom slab and floor. House 4: A basement sealing. House 5: A waterproof basement.	25,000	1,200	50–95%
Experimental study by Maringer et al. (2001) in the federal state of Upper Austria.	Studied 5 houses in high radon; for the first time used an extended Blower Door method to determine building tightness and radon levels.	Two farm houses mitigated with active SSDS and a single-family house mitigated with passive SSDS	Radon level varied from 150 to 900 (Avg. 457) depending on location and seasons	48 and 233	90% and 50%
Quasi-experimental study by Paridaens et al. (2005) in Belgium	A house in radon prone area with very high indoor radon concentrations was identified with passive measurement.	Active sub slab depressurization with a radial fan.	1790	<200	90%
Quasi-experimental study by Vázquez et al. (2011) in Spain	Evaluated four construction models in two locations (underneath the basement slab and outside the foundation wall) and two ventilation	Sump depressurization with passive and active ventilation	Same for all 4 models: Basement 39400 and ground floor 6860	Combination 1 (C1): 1740 and 603; C2: 16600 and 3210; C3:	93–95%

(*continued on next page*)

Table 1 (*continued*)

Study Design, Citation, location	Population, Sample, Measures, Duration of follow up/Timeline	Interventions, Comparison	Baseline Radon Before Mitigation (Bq/m^3)	Outcome After Mitigation (Bq/m^3)	Effectiveness* (*measured as the percentage of difference between pre- and post- remediation radon level)
	(natural and forced) techniques studied for no less than one month.			409 and 368; and C4: 327 and 480.	
Experimental study by Akbari and Oman (2013) in Stockholm, Sweden.	A two-storey house renovated to conserve energy; a multizone dynamic simulation model developed using an Indoor Climate and Energy (ICE 4.0) tools and validated using measurements of energy for heating, ventilation and total energy use.	HRV (Heat Recovery Ventilator)	3582	27 (at the highest HRV performance level)	Almost 100% radon mitigation with 74% energy saving
Experimental study by Yasuoka et al., 2009 in Kobe, Japan.	In a 5 t h floor apartment having high radon concentration from the building material was tested for radon. Mitigated for radon with and without using the air cleaner as the case and control case.	Mitigated with two types of radon filters: a high efficiency particulate air filter (HEPA-filter) and a deodorizing activated carbon (carbon-filter).	Mean radon concentration, EEC andEF were 86 ± 10 36 ± 4 and 0.42, respectively.	In both cases reduction of radon (<15) was significantly lower (0.01 and 0.05 level)	Effective 95–99%
Experimental by Gao et al. (2008) Hong Kong, China.	Anti-radon coating was experimented in a newly constructed building.	Anti-radon coating for radon mitigation	Maximum and average radon level 130,000 & 86,000; and 100,000 & 63,000 for the case & control	Below the set action level 142 & 174	99.85%,

3. Results

3.1. Synthesis of results

The data from fifteen selected articles are synthesized in Table 1 below. These are followed by the narratives that answered the research questions. PICOS format was followed for the synthesis of most relevant articles that provided the citations in the first column.

Studies conducted around the globe employed diverse techniques to remediate indoor radon in both experimental model and residential houses. Table 2 and Table 3 below show the comparative effectiveness of different remediation systems and construction solutions used in the existing and new houses respectively. Appendix 1 presents a country-wise summary of radon mitigation methods showing varying degrees of effectiveness. Based on these review findings, the research questions are answered in the next section.

3.2. Review findings to answer the research questions

The objective of this review was to answer three research questions. Firstly, the findings presented above shows that most experimental and intervention studies conducted in Europe, Australia and North America with the active sub-slab soil or sump-depressurization system (SSDS) reduced radon level-up to 99% in existing houses initially having higher than the reference levels of radon. This method provides a consistent high radon reduction at a reasonable cost as compared to other passive methods (EPA, 1993). In areas where the installation of an SSDS is impractical, and a rapid radon reduction is needed, an alternate method, called sum-pump in the UK, is also proved 99% effective. Sump-pump is based on the same fundamental procedure for old houses such as dilution and pressure change and accomplished by an active pressure-modifying sump with an exhaust fan (Scivyer, 1993). Thus, it was found that overall SSDS (either soil or sump) is the most effective single radon remediation techniques for the existing houses. However, remediating existing houses with SSDS is always more expensive than installing a barrier method or radon-proof membrane during new house construction.

Studies of new construction indicate that achievement of the best reduction with a single method depends on careful consideration of specific characteristics of a house (Denman et al., 2002; Groves-Kirkby et al., 2006; Scivyer, 2001). The foremost technique for new houses is to place a radon-resistant membrane across the entire basement with caulking that prevents radon from entering along the walls at the forefront. In high radon areas, this is reinforced with sub-slab natural ventilation where the floor is suspended or with a passive sump below the level of concrete ground-floor. In either case, where the radon level is very high, a power-driven fan fitted to the sump can strengthen the system (Scivyer, 2001). However, radon mitigation in Alaska and colder areas in Canada proved to be more effective when sealing of basement with vapour-proof polyethylene membrane and caulking of sidewalls was combined with an SSDS (Seifert, 2009). Other radon mitigation techniques tested in the UK and other EU countries with variable levels of evidence for success are (i) ventilation: balanced heat recovery ventilation; active and passive indoor, and underfloor ventilation. (ii) house pressurization, (iii) simple sealing and (iv) radon-well.

Some Nordic countries like Sweden experimentally recorded 100% reduction of preceding radon level with Heat Recovery Ventilation (HRV) system, but it has been only 25–75% effective in general household use (Akbari and Oman, 2013). Nonetheless, it works only in airtight condition and suitable where an excessive winter condensation is to be averted. Likewise, Finland noted up to 80% effectiveness by employing the radon-well technique in both the existing and new buildings (Holmgren & Arvela, 2012). Where in larger buildings, an increase in ventilation rate proved to add efficacy. Such ventilation was achieved together with a heat exchanger to warm incoming air in the winter and to cool it in the summer. They usually construct radon well close to the

Table 2
Comparing effectiveness of different radon remediation methods in existing houses.

Systems	Methods	Effectiveness
1. Depressurization		
a) Sub-slab depressurization (SSDS)	Vent pipes made of polyvinyl chloride are placed into the soil underneath the foundation. Air containing radon moving through the pipes is exhausted actively exterior to the building with an exhaust fan set at the garage, outdoors, or in the attic.	The most effective radon mitigation recorded in Calgary, Canada (Stanley et al., 2017) was 97.5%; previously the effects noted in Quebec by Brossard et al. (2015) was 95%. Whereas in the USA (Boardman and Glass, 2015) the highest record was 96.5%. In Austria, radon mitigation using the same methods with active and passive ventilation system shown 90% and 50% effect respectively (Maringer et al., 2001)
b) Sump depressurization	A form of SSDS, where the sump pump used to drain water is capped and made to serve as a passage to move out radon containing air.	Effectiveness recorded in both Spain (Vázquez et al., 2011) and in the UK was almost perfect (99 to nearly 100%) with active ventilation (Groves-Kirkby et al., 2006).
c) Sub-membrane depressurization	A polyethylene barrier membrane used to cover the dirt floor at crawl space; thus, the sealed foundation prevents radon entry. A vent pipe is placed in the crawl space to draw radon-containing air and exhausted with the aid of a fan to the outside.	Effectiveness noted was 53% only with the membrane but once an active vent pipe depressurization added with the exhaust fan; effectiveness raised to 98% in the UK (Scivyer, 2001). Studies in Austria, the USA, Hong Kong and the UK supported these findings (Ennemoser et al., 1995; Henschel, 1994; Gao et al., 2008; Scivyer, 1993).
d) Block wall suction, another type of SSDS.	Fan and ductwork used to draw suction on the hollow interior cavities of a concrete block wall. It keeps the inner air pressure lower than that in outside; thus, draws radon gas from the soil and expel out before entering the house.	Studies in Austria found 50–99% effect in radon reduction with the block wall suction (Ennemoser et al., 1995)
2. Ventilation		
a) Active Ventilation	With an active air exchange (by fan, air conditioning, heat recovery ventilators) indoor-outdoor pressure gradient is created.	Moderate effectiveness (25–75%) noted in the USA (Henschel, 1994), UK (Groves-Kirkby et al., 2008; Marley and Phillips, 2001; Naismith et al., 1998; Wang and Ward, 1997), and Norway (Rydock et al., 2002).
b) Passive ventilation	Air exchange between indoor and outdoor is increased by keeping the windows and doors open.	In Finland, passive ventilation is considered when winter radon level remains <400 Bq/m^3 (Valmari et al., 2014). Less effective results with variability noted in the USA (Henschel, 1994) and Australia (Huber et al., 2001).
3. Other		
Filtration: HEPA (high efficiency particulate air) filter and HEPA with deodorizing activated carbon-filter	Both filtration methods (HEPA and carbon filters) act as air cleaner and can filter out radon progenies that are measured as a decrease in radon equilibrium equivalent concentration (EEC). In the control case, the experiment was conducted without using the air cleaner.	In Japan, the calculated effectiveness of decrease in radon EEC found significantly ($p < 0.01$) lower with both filters compared to the control cases; though health risk remained unclear due to the increase in unattached radon EEC fraction (Yasuoka et al., 2009).
Mechanical supply and exhaust ventilation (MSEV) with heat recovery compared with Mechanical exhaust ventilation (MEV) & Natural ventilation (NV)	In Finland, impact of ventilation on the indoor radon level was assessed through an analysis taking into account the height and volume of the house, natural pressure difference, infiltration and mechanical ventilation rate noted in houses with NAV, MEV and MSEV strategies.	Regression analyses of radon concentrations with these strategies showed MSEV to markedly reduce pressure differences and radon concentrations by 30% in typically airtight apartments compared to the MEV and NV. They also noted radon concentrations 30 % lower in the two-story houses than in single units (Arvela et al., 2014).
a) Sealing (alone)	Sealing of radon entry points in floors and walls of buildings by impermeable filler and sealants	Least effects (0–40%) noted in the UK (Naismith et al., 1998), USA (Henschel, 1994) and Finland (Arvela, 2001).

Table 3
Comparing effectiveness of different construction solutions to avoid indoor radon in new houses.

Systems	Methods	Effectiveness
Barrier Membrane		
Barrier membrane installed in 64 new houses during construction in Northamptonshire, UK (Groves-Kirkby et al., 2006) with barrier membrane. Compared the results with a study of post-construction remediation (Denman et al., 2002).	Radon levels measured in the main bedroom and living areas for three month using track-etch detectors.	The mean annual radon level went below the action level (200 Bq/m^3) in 40% of the new houses. Whereas the post-construction remediation found over 75% of houses below the action level.
With or Without Barrier Membrane and additional Block and Beam Protection		
Construction solutions for three different group of houses were: a) Protected floor with barrier membrane and walls with cavity tray and compared with b) unprotected floor (no membrane) and c) protected with additional block and beam floor (Scivyer, 2001)	Radon levels measured in a) 131 protected houses and compared with b) 245 unprotected ones' and c) another 89 protected with additional block and beam constructed from 1990 to 1994.	a) 96% protected houses found below the action level compared to b) 80% unprotected houses c) almost all houses protected with added block and beam floor remained below the action level. This supported previous UK study conducted by Woolliscroft et al. (1994).
Radon piping installed under the floor slab of new houses		
Finland requires radon preventive measures as a condition of construction permit (Valmari et al., 2014).	Radon piping installed under the floor slab that can later be activated if radon level goes over action level (400 Bq/m^3)	Maximum 45% effectiveness noted in in new houses compared to 24% in old houses after activation of the radon piping.

building and use a fan to exhaust radon gas. The efficiency of the well depends on the homogeneity of soil layers, soil permeability, moisture content, depth of the well and ability of the pump used. The well functions better only in coarse types of soil and one radon-well influences a distance of 20–60 m (Holmgren & Arvela, 2012).

In some areas where the radon level is comparatively low, ventilation of crawl spaces and closed basement rooms is proved enough. Where weather allows, the simple opening of windows can bring about a temporary reduction in indoor radon, but this is unlikely to provide a permanent solution (Holmgren & Arvela, 2012; WHO, 2009). Similarly, a study conducted by the US EPA (1993) showed that natural ventilation could reduce radon concentrations by up to 90% when a sufficient number of windows and vents were open, a solution impractical in cold countries.

Among other mitigation approaches, filtration has a relatively long history in mitigating the inhalation exposure from radon decay products. A variety of methods such as electro-filter, an air cleaner with a mechanical filter (Kojima et al., 1992) and high-efficiency particulate air filter (HEPA filter; Kranrod et al., 2009; Rajala et al., 1985; Yasuoka et al., 2009) have been tested. However, no significant effect is noted so far. Thus, the U.S. Environmental Protection Agency (2009) does not recommend air filtration as a measure of radon mitigation.

Evidence gathered by the WHO (2016) showed that an active SSDS along with placing a plastic membrane in between the basement slab prevented radon exposure by up to 98%. Whereas only active SSDS could avert radon gas up to 90%, and passive mitigation reduced indoor radon levels up to 50%. Similarly, when used separately, both the barrier membranes and block and beam constructions decreased the levels of indoor radon by up to 50%. Whereas, employing these together substantially reduced indoor radon levels up to 75%. It is suggested that any mitigation system used should reduce radon levels by more than 50% (WHO 2016). When using a passive system, it could be easily upgraded to an active mode once the radon level goes up. Also, the methods should be energy efficient, remove other soil gases, control moisture and eliminate mould in the basements. An SSDS together with radon-proof membrane shown to serve most of these purposes. Therefore, it was concluded that a combination of techniques is always more effective than any single mitigation system.

Second, people in the cold countries start closing their doors and windows and switching on the furnace from the month of October. This is the time radon gas begins to buildup indoors. The present review shows that most of the residential studies measured and mitigated houses from October onwards. Thus, considering the meteorological and seasonal rise and beginning of the indoor accumulation of radon gas, late fall (October–November) found to be the best time to test and mitigate a house for radon (El-Zaher, 2011; Schubert et al., 2018). On the other hand, the best time to test and install a mitigation system in a house while considering the economy of the cost is during new construction, and for the feasibility, it is the time when the house is up for sale (Letourneau et al., 1992). Because this is the time to endorse the regulations and as there is a flow of cash, it is easy to find an option to bear the cost either by including it in the mortgage or negotiating the cost of mitigation between buyer and seller (Warkentin & Curry, 2018).

3.3. *Factors affecting mitigation*

The prime factors worthy of consideration while planning for residential radon mitigation include building characteristics such as age (Naismith et al., 1998), geographic location (Hystad et al., 2014), geologic formation (building constructed on uranium-rich bedrock (Marley and Phillips, 2001); initial indoor radon concentration (Gunby et al., 1993) and amount of radon resulting from the construction materials (Groves-Kirkby et al., 2008), insulation and presence of double-glazing (Birovljev, 2005), soil conditions, weather and climate (El-Zaher, 2011; Gunby et al., 1993; Schubert et al., 2018). Among other fundamental factors are the suitable building site, standard foundation design and building materials as recommended by the universal good building practices (International Residential Code, 2017).

Indoor radon concentration reflects the balance between the rate of radon entry into a house from all sources and the amount of radon loss by natural radioactive decay and dilution through ventilating air (Wilson et al., 1994). More precisely, the rate of radon entry into a building is the sum of contributions from soil-gas (generally the primary source), release from the building materials in some areas (Schubert et al., 2018), water supply from well or borehole (Smith and Voutchkov, 2017), drinking water (Smith and Voutchkov, 2017) and combustion of natural gas used for heating and cooking (Mitchell et al., 2016). While radon entry into a room from building materials is essentially diffusive, entrance from the subsoil is pressure-driven (the effects of wind naturally generate a difference of few Pascal), indoor-outdoor temperature differences, and the use of heating, ventilation and air-conditioning systems (Schubert et al., 2018). On the other hand, radon loss depends on ventilation rate (units of air-exchange per hour) and to a lesser extent on natural radioactive decay (half-life of radon progeny ($\tau1/2 = 3.6$ days). Continued changes in meteorological parameters and residents' lifestyle (windows opening, exhaust fans, AC and furnace using) also influence these processes on a day to day basis (Font and Baixeras, 2003; Hystad et al., 2014; Janssen, 2003; Schubert et al., 2018). Thus, the intervention effectiveness depends not only on the initial radon level and radon-prone areas but also on the individual household characteristics and residents' behaviours regarding the opening of door and windows; and passing the time outdoors. Among other factors are the cost of mitigation, willingness to pay for the energy consumption, accuracy of diagnostic measures, design and installation of the system in proper time and location (Brossard et al., 2015). Therefore, while the planner of radon remediation should be cognizant of these factors.

Among the recent developments, Collignan and Powaga (2017) used a numerical ventilation model in France and considered the effects of variations from depressurization and air change rate in the indoor environmental conditions on the radon entry rate and on the indoor radon activity concentration (IRnAC). In the context of developing an indoor energy consumption policy, the results showed that IRnAC was strongly correlated with the variations in the air permeability of the building associated with the ventilation regime.

4. Discussion

This review noted that many countries with high radon areas around the globe start recognizing the importance of healthy indoor atmosphere more rapidly in recent years than ever as evidenced by their adoption of new building codes in the legislation. This requires builders to install a passive radon impermeable membrane in between the basement slabs during all new constructions to prevent radon entry from the soil to residential buildings. However, the review of intervention studies revealed that merely placing a passive membrane is not the most effective practical solution; rather this should be reinforced by some active methods like a power-driven fan fitted to the sump (Scivyer, 2001). Where in extremely cold countries, this combination of passive membrane and caulking does not provide effective remediation, rather placing sub-slab perforated pipe (SSDS) systems that can be activated with fans when radon level goes high especially in North America proved to be useful (Seifert, 2009). In existing old houses of high radon areas, effective mitigation of indoor radon is achieved with the combination of house-specific long-term stable mitigation techniques such as an SSDS combined with the sealing of basement cracks and openings (Boardman and Glass, 2015; Maringer et al., 2001; Stanley et al., 2017). As we observed, in all situations, there exists a useful solution to fix the indoor radon and thereby to decrease the prevalence of radon-induced lung cancer risk. This is unique for human health risk mitigation from the exposure to radon gas compared to any other environmental hazards.

As noted the selection of an effective mitigation technique is contingent on a group of geologic, architectural, climatic, atmospheric, behavioural, and socioeconomic factors. In the first place, the geologic condition where the house is built is crucial (Marley and Phillips, 2001). To evade this problem, builders can consult radon maps that clearly mark the areas with high radon level. It is also critical to identify the sources and routes of radon entry; it's building up and circulation; and how the building features relate to all these aspects. The mitigation systems reviewed have considered more or less these factors and attained a certain degree of effectiveness in reducing the level of indoor radon. However, no mitigation system could address all of these factors and reduce the entire amount of radon for a sustained period. Instead, a thoughtful blend of measures could only lessen the level down to the action level (varied from country to country from 100-800 Bq/m^3). This underscores the fact that there is a continuous discharge of radon gas from building materials, in case the flow from the soil is blocked entirely and permanently. Therefore, in no time one can be 100% risk-free. This indicates uncertainty of the risk and justifies ICRP's (2010) recommendation to mitigate indoor radon even at a lower level to keep the level as low as possible, not to eliminate as that is impractical (Vaillant and Bataille, 2012).

Studies showed that indoor radon is related to the age of the house (Barros-Dios et al., 2007). There have been innovative studies in recent years that included home metrics in radon assessment like the year of construction, type of building and foundation, floor and room sizes where radon level was measured (Stanley et al., 2017). They noted that new houses built after 1992 had radon levels, on average 31.5% higher than those in older homes (Stanley et al., 2017). Similarly, they found that homes with larger floor-plan size had greater slab shrinkage causing wider floor-to-foundation gaps; and higher vault ceiling had the greater potential thermal stack effect creating an enormous negative pressure at the basement level – these draw more radon gas indoor. Besides, they noticed higher radon levels in the basement and utility spaces due likely to reduced ventilation and proximity to radon entry points. Thus, they wondered that millennial home-engineering practices that seek energy efficiency with insulation could compromise air exchange and increase the mean indoor radon level (Stanley et al., 2017). These findings open up the avenue to explore more about the architectural, engineering and building metrics that interact with the environmental factors to generate evidence for designing more appropriate radon mitigation strategies.

While several factors are related to radon remediation, the focus was on the effectiveness regarding how much the system reduces radon below the action level. Although evaluating the cost-effectiveness was out of the scope of this review, a few cost-effectiveness studies came across the review. No study strictly followed any health economic model to evaluate the cost-effectiveness of a particular radon remediation technique. However, from the cost-effectiveness perspective, overall radon mitigation strategy is geared to target the most vulnerable houses in high radon-prone areas and to achieve mitigation during all new construction irrespective of radon-prone areas. Such strategies are considered more cost-effective and less disruptive than performing any mitigation after the house is complete. Studies with homeowners in high radon areas provided further insight into their intention to pay and noted that people intend to pay more for remediation when the risk was high and adequately explained (Spiegel and Krewski, 2002). This underscores the evidence-based information provision for the residents in high-radon areas. Commercially found that on an average installing a radon mitigation system in existing house costs about $ 3,000USD/€2634, but the cost of placing a radon-proof membrane within the basement floor with associated caulking of sidewalls during new construction always remains less than $ 1,000 USD/€ 878 (Home Advisor, 2018). These facts from the market correspond with the review finding that remediation during construction is far better than doing it later.

Though the cost of mitigation may not be a significant financial burden for some, public support fund can certainly encourage low-income households to mitigate their houses for radon proactively. In the review, a break of silence was heard on this issue especially in many European countries (Norway, Denmark, Sweden, Switzerland, Finland and the UK) and some of the US states. Although seven Canadian provinces and all three territories have updated radon legislation, Canada does not use either spending or taxation powers to assist citizens with the cost of radon mitigation. However, most jurisdictions who adopted radon legislations (Canadian Environmental Law Association, 2018; National Conference of State Legislatures, 2015; Stationery Office, 2008; Valmari et al., 2014) suggested: a) disclosure of known radon hazards upon the sale of the property. b) Certification for mitigation contractors, c) surveying radon concentrations indoors. d) Issuing the license for radon industry. e) Inclusion of passive radon resistant construction. f) Provision of public education, testing, training, technical assistance, remediation grants, and loan or incentive programs and g) construction permit requires consideration of radon preventive measure. Consequently, homeowners became more active in testing but in cases over 53% of them are not mitigating their existing houses due mainly to financial cause, followed by other reasons like insufficient guidance (19 %), unavailability of radon professionals (12 %) and deeming unnecessary (9%; Valmari et al., 2014). Therefore, a reasonable next step for the federal government of Canada would be to expand the National Radon Program to provide financial assistance for the costs of radon mitigation to those in need of support. If done, this will send a powerful message that the problem is taken seriously, and a significant barrier is removed.

Finally, where perfect installation should ensure a significantly lower radon level in a home, in practice, error in installation or damages during construction or shrinkage of the basement with time can result in ineffective protection. This warrants training of radon mitigation personnel and builders as well as the need for post-remediation testing. The studies by both Long et al. (2013) and Valmari et al. (2014) showed that radon mitigation efficiency relates to the initial radon level. This underscores the importance of using different mitigation techniques based on the high (21% of homes exceeded the reference level) and low-risk areas (0.5%–4% of houses above the reference level). This also supports the utility of a valid radon map developed on the ground in selecting the mitigation option. Most of the habitations in Canada are built over the Canadian Shield – the high-radon zones. Future construction of buildings can consider incorporation of the radon-prone regions in the land utilization maps to avoid the hazard from the outset.

Further research can investigate the differential contribution of identified factors on indoor radon level and their impacts on the effectiveness of different radon mitigation systems. A qualitative study can explore residents' preference for and satisfaction with the mitigation systems in terms of their functionality and maintenance. It is still unclear how long a mitigated indoor environment will be adequately protected. The wide variation in effectiveness indicates that some of the mitigation systems are failing for various reasons. It is also likely that the effectiveness and efficiency could be enhanced by improving the methods, regular inspection, re-testing and maintenance protocols (Long et al., 2015; Rahman and Tracy, 2009). It is yet to determine how often the radon levels in a mitigated house be re-measured - yearly, biannually or in a five-year interval? Thus, accredited training of radon professionals-architects, engineers as well as constructions workers and property managers. These are to be implemented at two different levels to achieve these objectives. Again, despite the technical success of mitigation systems, only a small fraction of buildings with excess radon are currently being mitigated. Resounding the remark made by Rahman & Tracey (2009), recent experimentations in the area forecast innovation of some inexpensive mitigation techniques very soon for them to be accepted widely by the residents of high radon areas.

4.1. *Limitation*

The effectiveness was considered in terms of a remediation technique's ability to reduce radon below the action level. As no article was found that conducted cost-effectiveness of any radon mitigation system following the health economic models, no economic evaluation of mitigation measures was considered. There is an abundance of experimental studies done in single model houses or intervention with a few houses; thus, generalizing the outcomes to the broader housing population was difficult. Besides, there were very few studies that exactly followed the specifications mentioned in the new building codes for the residential building adopted in Canada and elsewhere recently. Future review with studies on the implementation of new building codes would provide updated evidence. To avoid reporting bias, documents were searched from grey literature, looked into the reference lists of selected peer-reviewed articles and contacted authors for further data. While selecting articles, publication status was not considered; thus, conference papers, reports and even articles in the press were included. However, there remains the possibility of publication bias as selective findings were reported regarding the effectiveness of mitigation systems while some articles investigated other topics, not within the scope of this systematic review. A last moment search was made in December 2018 to find the latest evidence to corroborate findings presented in the discussion section. This is to ensure that there was no risk of incomplete retrieval of the relevant and most latest research on the topic.

5. Conclusion

There exist effective solutions to reduce the human health risk from environmental exposure to indoor radon; thereby, to decrease the prevalence of radon-induced lung cancer. Some duly tested radon mitigation systems were identified that could effectively reduce radon in both new and existing houses. Thus, it was concluded that in existing homes, the active radon mitigation systems are more effective than the passive ones. The active sub-slab or sump depressurization system (SSDS) is the most effective of all remediation techniques reviewed. The active ventilation measures are the next most effective; passive ventilation was less successful. Contrary to the new building codes, placing a passive barrier membrane alone has found inadequate in the newly constructed houses. The review indicates that in high radon areas and for larger buildings, effective mitigation of indoor radon can be achieved with a combination of house-specific long-term stable mitigation techniques rather than using any single measure, particularly in the extreme cold countries.

The best time to test and install the mitigation system in a home is during late fall (October–November). Some of the identified factors worthy of consideration while planning for mitigating dwellings for radon are initial radon level, design of the building, geographic location, underlying bedrock, soil conditions, nearby water drainage or river system, weather and climate of the area. As there is not enough evidence about the long-term viability of any radon remediation technique, periodic radon measurement is recommended after remediation to ensure that concentrations continue to remain below the action level. For the practical implementation of radon mitigation in the future, training of the constructions professionals, information provision for residents, the establishment of public funds, incorporation of radon-prone areas in the land utilization maps, and enacting building codes deemed essential.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and writing of this article. A systematic review protocol was developed jointly by Selim M. Khan (first author) and James Gomes. These first two authors searched literature separately, met regularly to discuss document selection and their final inclusion in the review. The first author prepared the manuscript, but it was critically reviewed, and feedback provided by the second (James Gomes) and third (Daniel R. Krewski) authors. All agreed with the final version of the manuscript and gave consent for publication.

Funding statement

There was no funding source for this systematic review Thus, there has been no role of any funder on this work.

Competing interest statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2019.e01737.

Acknowledgements

The authors acknowledge the invaluable technical support from the McLaughlin Centre for Population Health Risk Assessment, University of Ottawa in designing the systematic review. Thanks to Michael Boutet (librarian) for his extensive cooperation in searching documents through the University of Ottawa library web portal. Thanks to my colleague Nicole Bergen for pre-reviewing the manuscript.

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