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Review

A Systematic Review of Radon Risk Perception, Awareness, and Knowledge: Risk Communication Options

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Abstract: Radon is the second leading cause of lung cancer after cigarette smoking, and research on individual risk perception of radon is crucial to prevent its health effects. In this work, we aimed to systematically review the scientific literature that has analyzed radon risk perception, awareness, and knowledge to provide insight on communication actions. For this purpose, following the PRISMA 2020 statement, we searched PubMed, Embase, and Web of Science, focusing on articles published since 2010. After the screening process, we included 40 articles, of which 5 explored only knowledge, 11 added risk perception, 11 further investigated the willingness to make radon measurements, and 13 examined the full cycle of prevention, including risk mitigation actions. Many articles performed a quantitative assessment of the relationship between knowledge/awareness/perception and actions such as radon testing and remediation, showing positive associations and providing interesting elements for evaluating interventions. Furthermore, citizen science actions described by some studies could be crucial for enhancing community self-sufficiency, responsibility, and the quality of preventive actions. To conclude, risk communication can play a key role in making risk prevention possible by reducing exposure, and a multidisciplinary approach, involving constant collaboration with different experts, is essential.

Keywords: radon; awareness; knowledge; risk perception; risk communication; risk management

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1. Introduction

1.1. Background

Radon is a natural radioactive gas that is present in buildings and is the second cause of lung cancer after smoking [1,2]. For this reason, many countries have issued regulations or recommendations to limit radon concentration levels in workplaces and at home.

In 1988, the International Agency for Research on Cancer (IARC) listed radon and its decay products as Group 1: substances that are definitely carcinogenic to humans [3].

The perception of radon risk is of scientific interest due to its important role in lung cancer onset in the general population (attributable risk: 5–20%), ranked by the World Health Organization as the fifth leading cause of mortality in 2010 [1,4,5]. Radon exposure can contribute to other carcinogenic effects: the respiratory tract is the primary target, followed by the skin, and several studies have reported an association between radon presence and skin and blood cancers [6–9].

A study of an accurate database of national radon exposures for 66 countries estimated the lung cancer mortality attributable to radon. In 2012, there were an estimated 226,057 lung cancer deaths attributable to radon (an average of 3% of total cancer deaths) worldwide, confirming that residential radon is responsible for a high share of mortality due to this disease [10].

1.2. Risk Perception and Communication

Risk perception has been studied from multiple perspectives, including social studies, anthropology, and medical disciplines, with psychology playing a primary role. Two main dimensions are involved in risk perception: a cognitive dimension, related to knowledge and understanding of risk, and an emotional dimension, which includes feelings; both are components of the reaction to risks, representations of immediate and/or future consequences and their implications, and how people decide how to behave accordingly. Slovic, arguing about the well-known psychometric paradigm, states that experts and the general public are necessary in the assessment process and that comprehension of public perceptions is crucial for effective decision making [11]. Perceived risk is therefore quantifiable and predictable: the psychometric paradigm has helped to clarify how certain elements and characteristics are specifically influential in people's perception of the dangerousness of an activity, such as controllability, voluntariness, threat to future generations, and responsibility [12].

In real life, the way people judge and evaluate risks is based on a combination of psychological and socio-cultural factors that shape their behavioral responses. There is no single way to process, understand, and react to risk information, as implied by one-way communication models. Therefore, the assessment of risks and their level of acceptance are highly dependent on attitudes and culture. These factors are influenced by differences between reference social groups within the same culture, resulting in different ways of understanding and responding to risks [13].

The psychological perspective is crucial to understanding the public's response to radon risk, particularly risk perception and management [14]. Indeed, rational behavior in which people receive information about the health risk and possible solutions and then simply apply them is unrealistic and rarely occurs. The process is more complex and "people may respond to health risk information in sub-rational ways, and such responses reflect both powerful unconscious and intentional psychological processes" [14–17]. Different hazards can have an impact on people depending on exposure and then become a risk, i.e., a measurable probability. Since risk perception is the process by which individuals attribute meaning and establish values to various threats, perceived risks are then informed by personal life history and past experiences in a specific community, shaping heuristics, which shape the approach to reality [18].

Various models and heuristics have been proposed to examine collective and individual responses to risks, which are useful for interpreting and placing risk perceptions in context in order to propose and promote effective risk reduction strategies [19–22]. The heuristics are: availability, i.e., the tendency to judge the probability of an event based on memories about similar facts (e.g., the association between cancer and radon); representativeness, which has to do with judgments about the probability of an event based on experiences or hypotheses (developing lung cancer at home is not part of the hypotheses or experiences); unrealistic optimism (e.g., when people are convinced that it cannot happen to them; in the case of radon, also due to an emotional attachment to the house, which generally gives a sense of security) [18].

Knowledge and its transmission focus on the importance of the social context: risk must be contextualized. If there is a lack of collective memory and knowledge, these can be built with appropriate tools and sharing, as some practical experiences show, even if related to risks of a very different nature [23]. Defining an area as a risk area could facilitate the public's acceptance of information or their curiosity and desire to receive comprehensive information that includes prevention. Risk perception and risk communication are indeed closely related. Communication can shape perception, and risk perception determines how and whether risk is communicated to communities. It is important to promote the construction of clear and reliable communication strategies, able to create effective messages, deliver them through the most convenient and relevant channels, and receive feedback [24].

Communications about health and environmental hazards tend to focus on the cognitive (rational and information-related) aspects; however, research shows that individuals' actions are also driven by the emotional aspects of risk. Information is the driver of behavior only if it is able to overcome the many biases that individuals have in processing risk information. Some psychological mechanisms, when risks threaten, drive people to action; others drive them to inaction. The radon hazard, due to its specific characteristics, can easily be downplayed to justify inaction. The perception of radon risk is subject to unconscious, cognitive, and emotional biases that influence the way information is processed: radon risk is perceived as distant, uncertain, and easily taken for granted; these biases may act to minimize risk perception [25].

Given these premises, it is not surprising that radon hazards fail to promote appropriate precautionary behavior: there are no immediate risks, and radon-related lung cancer occurs in the distant future. A multidisciplinary approach, involving continuous collaboration with experts in the field of psychology, is deemed essential to solve the problems associated with the lack of radon remediation. A key challenge for risk awareness programs is to inform the public in a way that does not create apathy, complacency, or overconfidence, without creating undue stress or alarmism [14,26,27].

Perceptions of radon risk were compared with perceptions of other sources of radiation risk, such as X-rays, nuclear energy, and nuclear waste. Individuals evaluate different types of radiation risk very differently. People perceive nuclear energy and what comes with it as a very high risk, while other sources, such as medical X-rays and natural radon gas, are considered to be of little risk. Most radiation experts see things differently. This perception gap shows that the acceptance of risk is conditioned by trust in those responsible for the technology and the evaluation of its benefits. The differences between the perceptions of lay persons and experts cannot be attributed only to the degree of knowledge: better information/communication about the possible consequences of radiation is needed [28,29].

Radiation risk is associated with a collective imagination linked to bombs and disasters: a risk that has no boundaries, penetrates the body, the environment and food, and never ends. As Slovic argues, "the lack of concern about radon seeping from the ground beneath dwellings seems to stem from the fact that it is of natural origin and occurs in a comfortable and familiar environment, with no one to blame"; moreover, it can never be eliminated completely. The public's perception of risk and its acceptance are determined by the context in which radiation is used. Different uses provide information on the nature of perceptions and factors determining risk acceptability [29]. The social context matters in perception, because of its particular history, of how the interpersonal network responds to risk, of the norms with which the group identifies itself, of the type of information circulating, and of the trusted people who exist. If there is no collective action on radon, it is difficult for anyone to take the initiative on their behalf [30]. In communicating the radon risk, people should understand that there is a danger and deal with it. However, the fact that it is serious and relevant may frighten people and create awareness denial reactions; people at risk may be the most difficult to persuade if the message is too frightening.

It is interesting to note here that even the scientific world has not always been unanimous about the radon risk. In the late 1950s, this danger was unknown to most scholars, when Bengt Hultqvist performed the first set of radon measurement in an indoor environment in Sweden. During the 1970s, a quantitative estimation of lung cancer was calculated for miners exposed to radon, and the interest in indoor radon increased, but only in the 1990s epidemiological studies developed risk estimation on radon in dwellings and lung cancer [31].

There is still a scientific controversy about radon risk. There are thermal baths all over the world that are advertised for beneficial treatments in radon-rich waters, and radon has been used for medical treatments. This issue has been addressed in depth by a recent analysis of websites advertising spa treatments, trying to understand how such messages may influence public perceptions about radon [32]. Controversies in the scientific world are part of the knowledge landscape concerning many health risks caused by environmental

determinants and certainly complicate the task of the authorities responsible for protecting public health [33].

For all those reasons, the research for the implementation of evidence-based radon communication programs is progressing rapidly: a recent paper proposed The Potsdam Radon Communication Manifesto in eight key steps to promote radon communication, based on the results of studies and experiences developed to date [34].

1.3. Regulatory Aspects

Although our review does not cover the analysis of the relationship between regulation of radon in dwellings and knowledge/awareness/willingness to remedy, some elements on regulation are given below. Many countries have issued regulations or recommendations to ensure that radon concentration levels do not exceed certain threshold values. The recommendation published in 1990 by the European Commission (CEC 90/143) indicated a reference level for radon of 400 Bq m^{-3} for homes, beyond which remedial actions to reduce radon concentration were recommended. Following the results of numerous epidemiological studies conducted two decades earlier, in 2009 the World Health Organization proposed a reference level of 100 Bq m^{-3} to minimize health risks from indoor radon, adding that if this level could not be achieved due to country-specific conditions, the chosen reference level should not exceed 300 Bq m^{-3} [1].

The World Health Organization report had a significant impact in the process of reviewing international regulations [35]. In particular, with regard to Europe, a reference level not exceeding 300 Bq m^{-3} was included in the European Directive on radiation protection (2013/59). Consequently, the 400 Bq m^{-3} reference level included in the European recommendation of 1990 must be considered outdated. According to the 2013 Euratom Directive [36], radon is an indoor pollutant monitored in workplaces and homes, with established limits and exposure control obligations.

Although public authorities in the United States focused on the problem in the 1990s and plans exist to address it, recent research shows that exposure continues to be very high in some situations. This is the case in many other countries in the world [37–39].

As a general remark, it is important to emphasize that the "reference level" is based on a much more complex concept than the previous "action level". In fact, whereas the "action level" established the radon concentration above which corrective measures had to be taken, the "reference level" represents a guide to optimizing exposure, primarily above the level but also as an indication below it. These concepts and the associated operational guidance for protection against radon exposure are particularly important for the implementation of regulations in the highest risk areas [40].

1.4. Objectives

This review aims to provide an overview of the research on radon risk perception, highlighting some of the challenges that risk communicators face in increasing testing and remediation of places with indoor radon pollution, in particular: investigation of public knowledge and awareness; analysis of risk perception, including psychological aspects; communication tools (information and action) for different audiences; risk governance tools and decision science; specific educational tools.

2. Materials and Methods

For the present systematic review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was adopted [41].

2.1. Search Strategy

This review was performed by searching three electronic databases, PubMed, Embase, and Web of Science. Radon, perception, awareness, knowledge, and perceived risk were the keywords in the following search query: "radon" AND ("perception" OR "awareness" OR "knowledge" OR "perceived risk"). Studies written in English were included and reviewed;

letters to the editor and abstracts were excluded. The search of the three databases was conducted without any time limitations on 22 January 2022 by G.D. The total records without duplication were 688 without temporal limits; 539 from 2000 to the present; 401 from 2010 to the present (183 from PubMed; 227 from EMBASE; 331 from Web of Science). Papers published from 2010 onwards were included in this literature review; this choice was made to understand the situation in the light of the most recent directives at European and world levels on radon and health.

Intense investigations into radon began as early as the 1990s, due to the intense radon monitoring activity carried out in particular by public authorities in USA and the need to promote public awareness for prevention. One of the leading researchers in the field of risk perception, Peter Sandman, described the response to radon in 1987 as "apathy and disinterest" [42], while in the same year, the Environmental Protection Agency reported it as "the most serious environmental hazard threatening Americans" [43]. In the 1990s, many studies reported on community awareness programs. The results in USA were mixed, with awareness being spread mainly among the more affluent, white, and highly educated. However, it was not easy to find people who knew the link between radon and lung cancer, while people were often convinced that it caused headaches, confusing radon with carbon monoxide. In fact, Vogeltanz-Holm and Schwartz's review, which mainly reports studies from before 2010, suggested a thorough revision of the information in circulation, because most of the studies reviewed reveal limited and erroneous knowledge [43]. Studies based on the psychometric paradigm were also set up in the 1990s [11,25,44–46], while questions were being asked about the different perceptions emerging among ordinary citizens and experts on risk issues [28,42,47]. Communication campaigns began to be structured and evaluated, and the foundations of the knowledge that we will see illustrated in the following pages were laid at that time.

2.2. Criteria for Eligibility and Inclusion Criteria

We have included studies that yield new results regarding the topics of interest: radon risk knowledge analysis and public awareness; analysis of radon risk perception, including psychology.

The main inclusion criterion was the presence of new research with original data collection on radon risk perception, awareness, and knowledge.

Examination of the 40 selected articles revealed differences in the consideration of conceptual dimensions related to risk [48]. The conceptual dimensions of perception provide information on the scope and extent of the analysis carried out in each scientific work, differentiating: understanding related to knowledge and sensory perception; reactions related to psychological consequences and further elaboration of understanding; reactions based on physical consequences or elaboration of the risk of physical consequences; and new behaviors originating from the understanding gained. This implies the inclusion in the analysis of each paper the presence of risk communication tools, educational resources, risk governance procedures, and policy recommendations.

2.3. Study Selection

Four researchers, who are among the authors of the paper (L.C., E.B., G.D., and O.C.), independently evaluated titles and abstracts on the basis of the eligibility criteria. The articles selected by the four reviewers were utilized in the next phase, when the full text was read. All authors carefully read the articles in the first phase and decided whether or not to include the papers. In case of conflicts, the four authors discussed together and, if no agreement was reached, a fifth author (F.B.) expressed the final judgment. The selection process is shown in Figure 1, which utilizes the flow chart provided by the PRISMA guidelines.

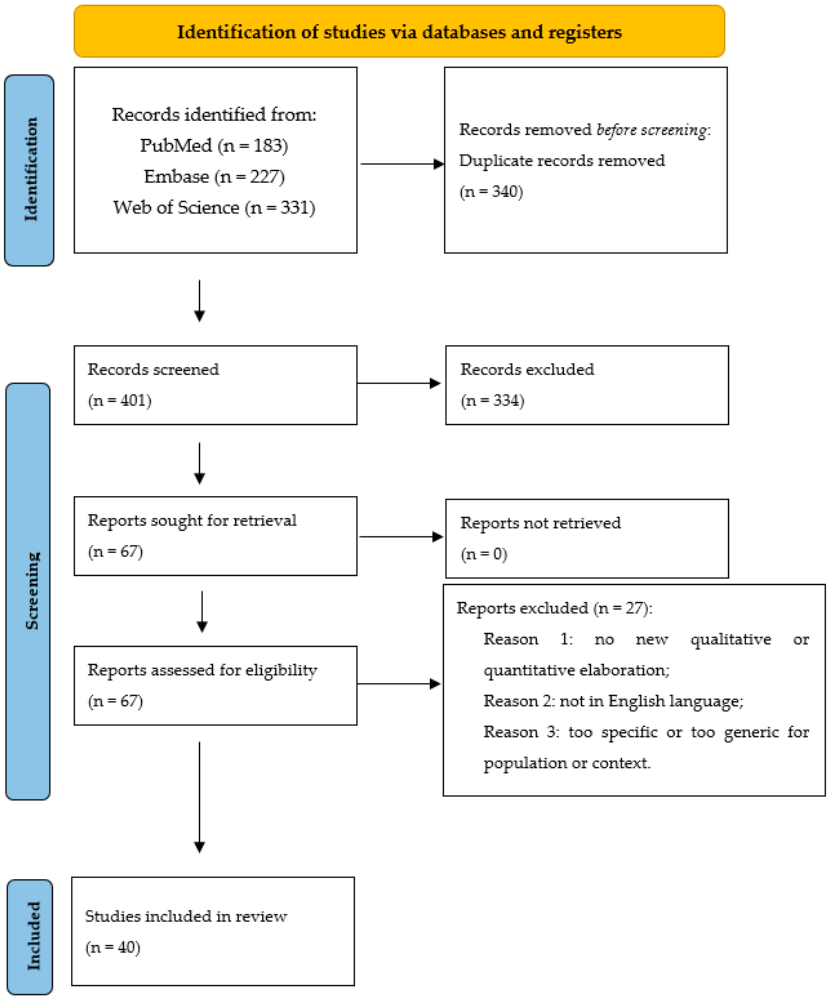

Figure 1. PRISMA 2020 flow diagram [41].

2.4. Data Extraction

Relevant features were extracted; specifically, the following information was considered: the methodology; the characteristics of the participants involved in the study; whether specific issues were included to investigate radon risk knowledge and public awareness; the analysis of radon risk perception, including psychology; which tools were used in radon risk communication tools (information and action) to different audiences; governance tools for decision science; radon risk-specific educational tools. These relevant data were included in a table form to obtain a synthetic overview of all the articles read in full by authors. This table format enabled the authors to complete a cursory overview of the materials.

3. Results

The results of this systematic review are presented in the following paragraphs to highlight the characteristics of the selected articles, the geographical and temporal distribution, the study design, the population involved, and the methods used. Then, an analysis is made of the key topic on which the 40 selected articles produce original knowledge: the first key topic is the perception of risk and its conceptual dimension, which includes knowledge, awareness of the danger, risk perception, and willingness to take action to measure radon and to control its presence; the second key topic is the communication of this same risk and the educational tools mentioned in the selected articles; the third key topic is the recommendations produced for policymakers and risk managers.

3.1. Search Results and Study Characteristics

The flow diagram in Figure 1 describes the article selection process that was followed to incorporate the studies in this review. A total of 741 (183 + 227 + 331) articles were identified by searching the three databases mentioned in the Material and Methods section. From these initial records, 340 duplicates were removed, leaving 401 papers for further review. The number of included studies was reduced to 67 after screening the titles and abstracts and applying the following exclusion criteria:

- Generic studies;
- Editorials;
- Studies without original findings;
- Studies where there was no indication for risk communication strategies.

The remaining articles underwent a full-text evaluation, bringing the total number to 40 published articles. Table 1 summarizes the main characteristics of the studies included in this review, in reverse order of publication.

3.2. Geographical and Timeline Distribution

Figure 2 shows the geographical distribution of the surveyed countries. In the United States, where 21 of the selected studies come from, the radon risk is well known to experts and has been studied since the 1980s, including risk perception and risk communication. However, the legislation is not uniform: 29 states require disclosure of radon levels when selling existing homes and 23 require radon abatement in the construction of new homes, but no state requires homeowners or renters to inquire about radon levels in their homes [49]. Six articles reported studies developed in Kentucky, a US state with high levels of radon, smoking, and lung cancer incidence; residential radon levels are also above the US Environmental Protection Agency's action level [50]. These studies are more comprehensive in that they systematically address the risk posed by radon, smoking, and second-hand smoke, both separately and in synergy, and address the entire cycle of radon prevention and management, from knowledge to awareness, risk perception, testing, and remediation, and also address learning from experience, empowerment, and training [50–55]. Nine articles were based on research in the European Union [30,56–63], including four from Italy [59–62], and ten from the rest of the world [64–73], including four from Canada [70–73] and two from Turkey [64,66].

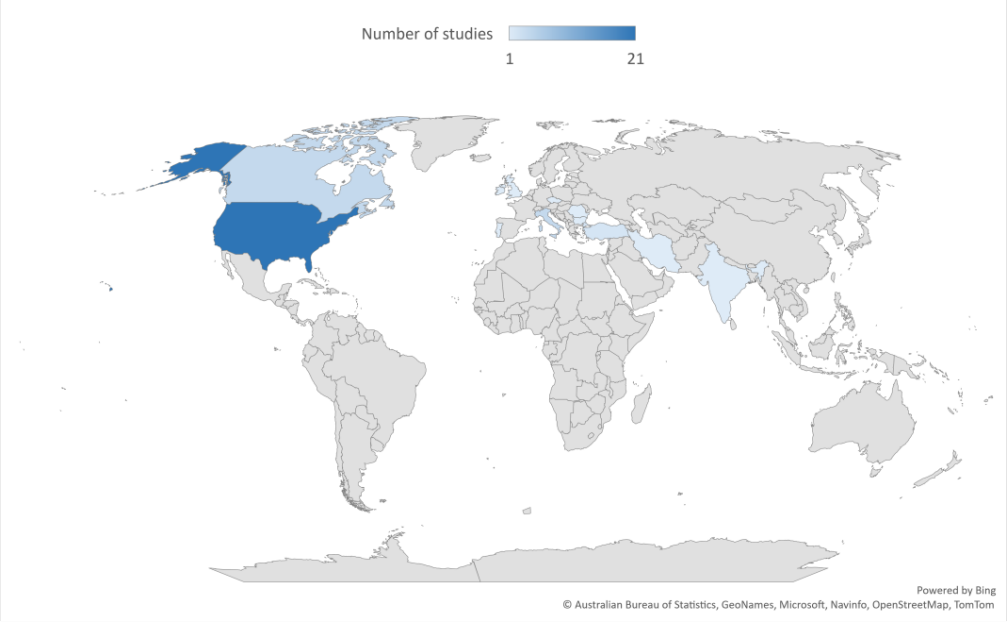

Figure 2. Geographical distribution of the studies included in the systematic review.

As shown in Figure 3, there was an increasing trend in the number of articles published in the last decade, which highlights the growth of this research field.

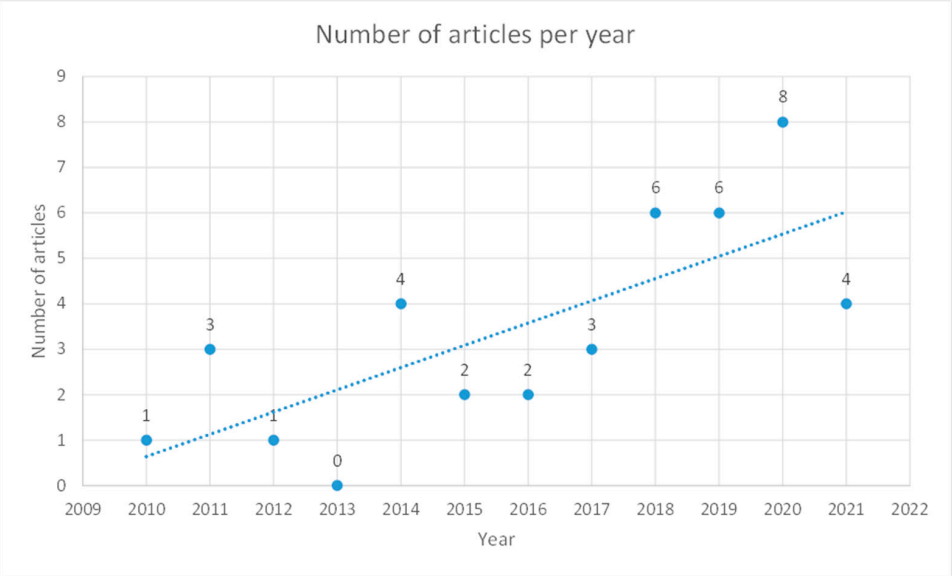

Figure 3. Timeline distribution of the articles included in the systematic review. The blue dashed line represents the increasing trend of the annual number of published papers.

3.3. Study Design and Population

The selected studies were mainly cross-sectional studies and survey studies—Internet [58], mail [74], face-to-face [75], and telephone surveys [76,77]. Within the survey studies, the sample size varied between a maximum of 6653 [77] persons involved and a minimum of 35 [71]. The studies used quantitative [30,49–52,54,57,60,63–71,74,75,77–82], qualitative [56,72,83], and mixed quantitative and qualitative methodologies [62,73,84,85], and some were aimed at evaluating an intervention [52,53] or a risk communication tool [63,86]. The qualitative method can enable researchers to go deeper into understanding the individual and collective factors influencing risk perception and capture subjective and objective aspects of radon risk perception, communication, and willingness to address the problem.

The population included was an interesting element to observe. Twenty articles reported data on the general population [30,49,52,57–59,61–63,65,66,70,71,75–78,80,81,84], in two cases as part of a radon testing program [53,78], in one case among people interested in testing [70], in one case together with a group of experts [79], and in one case with a group of home buyers [56]. Ownership was an important element, as radon risk remediation actions should be the direct responsibility of the owners, and in some countries, information on the presence of radon in the home was part of the requirements for marketing houses [49]. For this reason, home sellers [83], home buyers [56], homeowners [50,54], and homeowners with tenants [51,70,72,73] were interviewed, in one case to carry out radon tests and a medical check [51]. The health protection sector was considered as a player in the dissemination of information to patients, as an actor in prevention, and as responsible for the ability to identify risk factors and a means of prevention. Three articles examined health professionals and family doctors [67,82,87]. One study found parents and carers of children selected for smoking and non-smoking at home [52]. Finally, the education sector was included in the studies developed: six articles involved students from different schools from the age of 16 up to graduation; in two cases, interviews were conducted with the students' parents. In summary, investigations were conducted through the use of questionnaires targeting the general adult population and/or specific categories such as:

- Family physicians [82]; public health educators, health officers, nurses, environmental health specialists working in public health departments [87]; health professionals [67];

- Medical students [68]; university students [64,86]; high school students [59,60,62]; parents of students aged 5–18 [85]; teachers [59]; households [69];
- Home buyers [74]; adult homeowners [50,55]; and renters [55].

With regard to the representativeness of the surveys, i.e., of individuals in the samples reflecting the characteristics of the entire population, the results of the studies are limited when the samples are small and determined by convenience sampling. Three studies selected participants using random sampling, thus increasing the generalizability of the results [64,69,76]. Several authors clearly pointed out these limitations in the discussion, pointing out that voluntary participation and survey methodology may have introduced bias into the overall results [30,70,75,82,86,87]. Furthermore, surveys conducted online [73,87] and on social networks such as Facebook and LinkedIn [63] may not have included participants from different demographic and cultural backgrounds, which may have biased the results. Three studies recruited participants at public events [59,61,85], and one study was constructed with focus groups [83], probably including only people with a high level of education and interest in science.

3.4. Key Topic 1: Risk Perception

The conceptual dimensions of risk perception and their increasing complexity were analyzed, from basic understanding and awareness to the perception of risk, the availability to perform radon prevention tests, and implementation of remediation actions.

In detail, all the selected studies assessed the knowledge about radon risk; five of them explored knowledge only [59,61,62,69,87]; 11 added risk perception [51,54,55,58,60,64,66,68,74,79,80]; 11 further investigated the willingness to make radon measurements in one's home [30,49,50,53,67,76,77,81,82,84,86]; 13 research papers examined the full cycle of prevention, including risk mitigation actions [52,56,57,63,65,70–73,75,78,83,85].

When there is no specific knowledge, or the questionnaires concern different types of environmental health hazards, the answers show that knowledge of the radon risk is low or very low [67,68,71,79].

The knowledge was found to be low when no prior information was circulated [57,62] and increased when associated with insights provided during interviews and training programs implemented [59–61,78,86]. Knowledge was also limited in high-risk areas, where information was available but clearly did not adequately reach the target population [69,77]. Information available about risk was even described as incomprehensible by the general public, and the knowledge appeared low as a consequence, which calls for accurate communication campaigns [58].

More articulated was the analysis of contexts in which information was provided, social networks or knowledge were activated, when action could be taken to carry out radon measurements, or when the health of fragile individuals, such as children, had to be protected. In these cases, the perception of risk turned into a willingness to activate and a choice to engage, together with the request to receive more information [51,56,66,85]; cognitive and emotional components were important to be considered, in order to understand protective behaviors [71,73], but also age and occupation differences in concern and actions [63]. It was observed that older men in high-level professions were the most likely to delay actions, while the younger, women, and parents were more concerned about radon risk [70].

The availability of tester devices and health monitoring by public administrations could support the decision to carry out radon monitoring and preventive activities [52,53,65,76,80,84]; risk perception, self-efficacy, and knowledge were also positively associated with intention to test [81].

In several studies, the association between perceived health risk and intention to test to understand one's exposure at home appeared clearly, particularly when educational level was higher and societal influences were present [50]. Ethnicity was associated with a lower level of awareness and risk perception [75], and economic factors could be determinants in some cases [49]. Interestingly, however, when the level of knowledge is sufficiently high,

optimistic bias may intervene, awareness may decrease, and the social dimension, i.e., what others do, becomes important [30].

In other studies, specific stakeholders who could influence radon knowledge and prevention were consulted. Home sellers were an interesting subject to investigate, in some cases with a positive role because they act as multipliers of available information [74,83]; realtors in states with radon policies generally expressed more positive attitudes toward testing than those in states without policies [83]. In the Czech Republic, in-depth interviews and focus groups were conducted with a group with high radon levels in their homes and a group that was going to purchase a home. New homebuyers and families with children were concerned: women in particular about health and men about technical issues. Influential elements mentioned that inhibited improvements were as follows: economic factors; widespread false beliefs, such as that radon does not hurt or that it is sufficient to open the window; most people were afraid to apply the necessary technical solutions [56].

Health personnel were found to be insufficiently informed and needed training and support to play an active role [82,87].

Radon risk has been recognized as the second leading cause of lung cancer after tobacco smoking, and the synergistic effect is a well-known cause of pathologies. Interestingly, in a considerable number of articles, the risk of smoking is mentioned and used in the analysis [64–69,71–74,77,80,82,84,87]. In Canada, the perception of the existence of a synergistic, social, and cultural influence and household concern were found to be significantly related to the intention to test for radon levels in the home, to perform a test, and to mitigate the risk; residents who had both cognitive and emotional risk awareness were motivated to take preventive action; family care, knowledge of others with lung cancer, and financial ability were favorable factors, while lack of awareness, home ownership, and cost of mitigation were barriers to preventive actions [72,73].

The synergist risk associated with radon, in particular, is mentioned and used to investigate and develop knowledge: recognition of a synergistic risk with smoking was a positive factor in increasing risk perception and protective behaviors [50–55,63,77,80].

A quantitative assessment of the association between knowledge/awareness/perception and actions such as radon testing and remediation could be crucial to evaluate health protection interventions. Nevertheless, only part of the studies provided a quantitative evaluation of these associations. Khan and colleagues investigated in two studies the relationship between perception variables (perceived susceptibility and severity of radon risk, synergistic risk perception, smoke at home, care for children, social influence) and intention to test, performance of test, and mitigation behaviors [72,73]. More specifically, it was highlighted that, whereas all the perception variables were associated with intention to test among homeowners and tenants, only two variables (care for children and social influence) predicted mitigating behaviors for homeowners [73]. Significant associations of perception variables with the willingness to pay and resident protection behaviors were also reported [72]. In Romania, a low awareness was associated with lack of adoption of mitigation measures [57]. In Colorado, USA, the effect of various outreach activities on the incidence of home testing and mitigations was evaluated: for home testing, a statistically significant association was shown, whereas for remediation actions it was not statistically significant [78]. A study carried out in Utah, USA, showed that risk perception, self-efficacy, and knowledge were positively associated with testing [81]. A study that used an APP for smartphones to communicate radon risk showed positive associations with radon testing [86]. Generally, having knowledge and awareness about radon and perceiving it as a risk had a significant association with willing to test, as demonstrated by the statistical analysis of several authors [30,50,65,67,70,85].

3.5. Key Topic 2: Risk Communication

In most of the studies reviewed, communication tools were presented, either as a component of the study or as an outcome. In several studies, direct community involvement was considered to raise awareness, explore risk perception, and build a culture of

prevention. A voucher to reimburse the cost of radon analysis was attached to a survey conducted in Kentucky. This expedient revealed that perceived severity, social influence, and education level were positively associated with the intention to perform a radon analysis at home, as hypothesized by the researchers; synergistic risk perception was associated with higher perceived severity [40]. In another case, in North Dakota, an APP was piloted in which students had the option of requesting a testing kit [86]; in Colorado, a pre-post-test in a training course, with the distribution of radon testing kits, obtained a positive result in that the full cycle of awareness and then remediation was completed by 25% of the respondents who had installed a radon mitigation system in their home [78].

The overall health risk associated with radon exposure may be difficult for the general public to understand. Most authors emphasized that there should be a clear separation between general messages and individual messages designed for each target group, that active communication in all channels, including social networks, should be intensified. Furthermore, it appeared necessary to take measures to increase the credibility of national radiation protection authorities. Another important issue that emerged was that it would be useful to increase collaboration with social science specialists, because effective risk communication requires cooperation among organizations and clear and coordinated messages and the engagement of speakers with good credibility at the community level.

Several research articles specifically explore the topic of risk communication, pointing to methods and strategies to increase public awareness and willingness to improve the situation inside buildings [56,58,63,71,75]. Knowledge and information tools were explored by D'Avino and colleagues in Naples, Italy: web searches and newspapers were found to be the most common sources of information among the resident population. They described initiatives of the students: public information events involving institutions and citizens, during which they administered the questionnaire. The study highlighted the profound impact of disseminating information about radon and its potential carcinogenic effect [62]. Lopes in Portugal evaluated a computer tool through a screening questionnaire to 873 people. In this work, an indoor radon risk exposure indicator was proposed, and an information technology tool was implemented and improved to increase the effectiveness of radon risk management [53]. Cronin and colleagues in Allentown, PA, USA, specifically demonstrated the need for radon risk communication strategies that were culturally appropriate and particularly targeted to the Hispanic population [6]. Allentown had some of the highest indoor radon levels in the country, but only a small portion of the population had tested in their homes. This was especially true among self-described Hispanics, who composed nearly half of the city's population [75]. Khan and Chreim in the Ottawa–Gatineau area of Canada examined the factors that enable and hinder preventive measures among residents to develop an appropriate risk communication message: enablers had a good understanding and were health consciousness, had a family to care for, and experience with illness and financial possibilities, while the obstacles were the lack of awareness and resources and no home ownership [71].

Makedonska and colleagues in Bulgaria [58] conducted an internet survey on risk perception (309 subjects), analyzing radon risk communication activities within the National Radon Program. The survey was conducted as a benchmark to assess public awareness; the main channels used to inform the public were publications on websites, magazines, interviews on local TV and radio, and local seminars: 80% had heard about it, only half responded well about the details, and only 5% trusted scientific institutions and organizations. As a follow up of the study, the researchers proposed essentially to focus the effort of prevention reinforcing communication activities [58]. In a study conducted in the Czech Republic, Fojtikova and Rovenska highlighted a possible way to improve radon risk perception and related actions: the use of health marketing that brings together traditional marketing theories and science-based prevention strategies [56].

One of the important evolutions in the relationship between science and society is the emergence of citizen science [88], where individuals and/or the community are engaged or required to perform investigations on their own territories. In the present review, several

experiences are reported that could be considered as citizen science examples, changing the way of communication from a top-down direction to more inclusive and interactive solutions. To be mentioned, the practice developed in the Campania Region by students was a work-based learning experience, where they involved family members [60] and projects where students and teachers organized public events and distributed questionnaires to collect data about radon knowledge and disseminate information on risk [59,61,62]. Community-based participatory research was developed in Massachusetts with the objective to empower residents in a highly vulnerable community with indoor testing; radon was measured among other parameters, and the information was used to provide the indication for undertaking preventive measures, during the report-back phase, in an environmental-justice perspective, where researchers recognized the obligation to transmit all the information regarding factors that directly affected personal health [84].

3.6. Key Topic 3: Recommendations

Most studies contained recommendations addressed to different actors, responsible for specific activities in governance and policy in different sectors.

According to three studies developed in the USA, the results of environmental monitoring must lead to mitigation and risk reduction actions. In order to accomplish this, stakeholders, including residents and those responsible for housing managers, should be involved from the beginning and share the parameters chosen and the knowledge obtained [80,81,84]. Multidisciplinary scientific collaboration and inclusion were referred by several authors who emphasized that communication could be more effective if it has a pedagogical character, enabling the receivers of the information to analyze and compare the different results and act accordingly [63]. Educational activities were recommended by many authors, especially when the level of knowledge was low [57,64,69,79,87]. Health marketing concepts could be used to manage radon risk, providing a segmentation of the public, identifying specific motivations, and explaining problems in depth [56]. Inclusion of multiple stakeholders with targeted education programs was strongly recommended, especially where risk awareness is lacking [65], and indicated the possibility for advertising campaigns targeted at individual actions [30]. The culture of cultural differences was advocated in the presence of multi-ethnic communities [75]. Cancer prevention campaigns have often been used to provide information and generate awareness about the radon risk [52,54,55,73,74,79,83], and specific suggestions were provided for protecting fragile subgroups [51].

Several authors recommend the inclusion of testimonials that can influence those most at risk in order to reduce the risks of exposure to radon and tobacco smoke, such as from health promotion professionals [52,55,56,86], real estate agents [75], and parents [74].

As a follow up of the study conducted in Bulgaria, the researchers proposed six objectives for a new radon action plan, recommendations that could be useful in many EU and non-EU territories: to gain broad organizational support and determine the need for risk communication; to develop objectives for risk communication with key messages for different target groups; to train and coach the communication team; to assess stakeholders and communication channels; to develop plans with different organizations for different stakeholder groups; and to evaluate the radon risk communication program [58].

A number of findings have been recommended as useful to increase radon monitoring activities in homes [50,51,79,80] and to support risk reduction practices [60,77], as well as the drafting of strategic plans for radon risk mitigation [69], considering—when possible—the cognitive and emotional aspects of perception and the responsibility of governments and residents to address the problem [72]. In some cases, legislation was already in place but should be strengthened [85].

Table 1. Summary of studies investigating radon perception, awareness, knowledge, and perceived risk.

Authors, Year	Study Area	Population Characteristics	Study Design Objectives	Results
Cholowsky, Irvine et al., 2021 [70]	Canada	2390 individuals	Survey of a convenience sample. Explore associations between demographic characteristics and (i) how people encounter and respond emotionally to radon awareness information and (ii) the influence of personal perceptions of radon knowledge and motivation for taking action.	Different groups of people encounter, react to, and variably take action after gaining radon awareness. This highlights the importance of developing targeted demographic messaging to create effective radon exposure prevention strategies.
Khan, Gomes et al., 2021 [73]	Canada	204 family physicians	Survey via a mailed questionnaire. To study radon knowledge and behaviors concerning radon among family physicians.	Most family physicians are knowledgeable about radon, and more than one-third have tested their own homes. However, only a minority transmit this knowledge to their patients.
Lopes, Nunes et al., 2021 [63]	Portugal	873 individuals	Survey presented through Google Forms. To evaluate the IRREI (Indoor Radon Risk Exposure Indicator), a tool designed to increase the radon risk communication effectiveness.	The IRREI is a simple and effective indicator for effective indoor radon risk exposure communication. A tool for communicating the radon exposure risk is more effective when it is implemented in an intuitive use tool, i.e., developed according to the green–yellow–orange–red color code, indicating levels of very low risk, low risk, moderate risk, and high risk, respectively.
Schmitz, Klug et al., 2021 [82]	USA, North Dakota	592 homeowners and tenants	Mixed method design: quantitative (n = 557) and qualitative interviews (n = 35). To explore the determinants shaping perception and actions of resident population.	Inducing protective action to reduce risk requires comprehensive population-level interventions considering dual perceptions of the risk that can modify the risk determinants. The radon health communication program would be more effective through addressing both these aspects of risk perception along with plausible regulations and necessary incentives.
Cronin, Trush et al., 2020 [75]	USA, Pennsylvania	551 individuals	Face-to-face survey. To (i) characterize the difference in testing rates between self-identified Hispanics and non-Hispanics, (ii) quantify the level of radon awareness and knowledge, (iii) identify potential obstacles to radon testing, and (iv) determine whether more effective risk communication is needed.	Individual and community understanding of the risks of exposure to radiation sources such as radon are dependent upon communication that informs and spurs appropriate action. This study demonstrates the need for culturally appropriate radon risk communication strategies targeted to a Hispanic population. Successful communication will raise awareness and knowledge that can lead to better public health protection.

Table 1. *Cont.*

Authors, Year	Study Area	Population Characteristics	Study Design Objectives	Results
D'Avino, La Verde et al., 2020 [62]	Italy, Campania Region	6705 individuals	Qualitative study through questionnaire administration. To assess the status of the knowledge of radon gas in the general population and high school students, in the metropolitan area of Naples.	The study highlighted the deep impact of the disseminating information about radon and its potential carcinogenesis effect; the results suggest revising the outreach campaign in order to spend more efforts to promote the sources of information that revealed more efficient to this aim.
Gleason, Taggert et al., 2020 [76]	USA, New Jersey	1000 residents	Questionnaire. To characterize the demographic and behavioral characteristics of the population practicing environmental risk-reduction behaviors in order to identify gaps in current prevention outreach efforts.	There is a need to improve rates of environmental risk-reduction behaviors and reduce disparities in the practice of these behaviors through efforts to increase awareness. Public health officials should target outreach to specific populations that do not practice risk-reduction behaviors.
Kim, Brewster et al., 2020 [86]	USA, North Dakota	97 undergraduate students	Pre-test–post-test design to explore the feasibility and effectiveness of an APP. To study radon knowledge, attitudes, and behavior relevant to radon testing before and after APP use.	A smartphone APP is a promising venue for communicating radon risk and for stimulating radon testing. Future interventions designed to increase actual test kit use are required to maximize the benefit of the APP.
Loffredo, Savino et al., 2020 [61]	Italy, Campania Region	293 individuals	Interviews to general population during two scientific events. To study radon-related awareness and perception.	The findings allow one to conclude that a higher educational level helps to achieve a good level of radon risk awareness. The results obtained suggest continuing and extending the study on radon risk awareness on a large scale.
Martin, Ryan et al., 2020 [85]	USA, Vermont	126 parents of K-12 children	Qualitative data interviewing two parents and questionnaires. To (i) assess knowledge of radon and associated health risks, (ii) elicit parent perspectives about radon in schools, and (iii) gauge community support for legislation mandating testing for and mitigation of elevated radon levels in schools.	Parents with elementary school children were significantly more supportive of radon testing, mitigation, and legislation than parents with only children in middle and/or high school. Parents with more knowledge about radon were significantly more likely to support radon testing in schools. Educating parents about synergistic risk could strengthen existing community support for legislation mandating radon testing and mitigation.

Table 1. *Cont.*

Authors, Year	Study Area	Population Characteristics	Study Design Objectives	Results
Nwako and Cahill, 2020 [87]	USA, New Jersey	386 public health personnel	Questionnaire. To explore differences in knowledge about radon gas exposure among public health workers.	The role of public health workers in disseminating information about environmental hazards to the communities they serve should be well-defined. Government agencies will have to combine efforts to achieve the long-term goal of the 1988 Indoor Radon Abatement Act. Training of public health workers about environmental hazards should be a priority to achieve the IRAA goal.
Stanifer, Rayens et al., 2020 [53]	USA, Appalachia rural region, Kentucky	58 adult participants recruited from two rural primary care clinics	Brief survey and administration of a free long-term home radon test kit. To compare differences in sociodemographic characteristics, personal risk perception of lung cancer, lung cancer worry, and synergistic risk perception among residents who completed home radon testing with those who did not.	Providing free home radon test kits in the primary care setting shows promise in prompting radon testing in rural Appalachia. Health care providers in rural Appalachia need to encourage patients of all ages to test their homes for radon, especially those who smoke or report smoking in the home.
Butler, Huntington-Moskos et al., 2019 [55]	USA, Kentucky	560 homeowners and renters	Single-item synergistic risk perception measure using five-point Likert-type scale. To examine the short-term impact of a personalized environmental report-back intervention to reduce home exposure to tobacco smoke and radon and explore perception of synergistic risk.	For treatment and control groups combined, there was a significant increase in perception of synergistic risk from baseline to 3 months, but the study groups did not differ. There was no association between perceived synergistic risk and whether or not there were smokers at home. Learning about combined risks for lung cancer, with or without dual home screening for second-hand smoke and radon and environmental report-back, may enhance perceived risk for combined environmental exposures.
Coppola F., Lo Verde et al., 2019 [59]	Italy, Campania Region	858 individuals	Survey conducted by students and teacher. To understand the level of risk perception for exposure to radon among the population.	The percentage of people who know the risk of radon exposure is from 35% to 41% in cities where training projects have been held for about 10 years, while in Scafati it is equal to 24%. The development, by universities and research institutes, of training projects with the involvement of local schools can make an important contribution to increasing the public awareness of the radon risk.
Khan, Krewski et al., 2019 [72]	Canada	557 homeowners and tenants	Face-to-face survey. To describe residents' perceptions of radon health risks and evaluate how perceptions correlate with protection behaviors.	Compared to the gravity of the risk, public perception remained low. Health risk communication programs need to consider the affective aspects of risk perception in addition to rational cognition to improve protection behaviors.

Table 1. *Cont.*

Authors, Year	Study Area	Population Characteristics	Study Design Objectives	Results
Khan and Chreim, 2019 [71]	Canada	35 individuals	Qualitative study with interview. To explore perceptions of radon health risk and examine the factors that enable and hinder the adoption of preventive measures among residents.	Risk perceptions are subjective and are influenced by micro and macro level factors. Inducing protective action to reduce risk requires comprehensive interventions considering the dual cognitive and emotional aspects of risk perception.
Losee, Shepperd et al., 2019 [49]	USA, Florida	159 individuals	Questionnaire. To experiment with a stronger manipulation of burden via resource demand and multiple measures of the availability of financial resources.	Higher resource demand (i.e., mitigation required USD 2000 vs. USD 200) and lower financial resources (via income and self-reported ability to pay for radon gas mitigation) corresponded with greater perceived burden of taking action.
Pugliese, La Verde et al., 2019 [60]	Italy, Campania Region	120 students	Survey. To educate students on topics such as environmental radioactivity and in particular about the public exposure to the radioactivity of natural origin.	The student could know and deal with the problem, in a realistic way, from the point of view of scientific research, thanks also to the Radiolab project of the National Institute of Nuclear Physics, through which measurements of the concentration of radon gas activity have been carried out in the buildings of their own school complex.
Davis, Johnston et al., 2018 [81]	USA, Utah	308 individuals	Questionnaire. To examine differences in beliefs about radon testing among radon testers (n = 110) and a comparison sample of residents (n = 198) in a high-level radon area.	Risk perception and knowledge were positively associated with testing. Behavioral modeling was indirectly associated with testing through intervening pathways of self-efficacy and knowledge. The results imply that increasing radon knowledge and self-efficacy, along with traditional intervention efforts focusing on risk perception, might be important factors to increase radon testing.
Makedonska, Djounova et al., 2018 [58]	Bulgaria	309 individuals	Survey via Internet. To assess perceptions and the level of knowledge regarding radon as a benchmark for evaluation of public awareness.	Health risk associated with radon exposure is incomprehensible to the general public. Clear separation of general and individual messages designed for each target group should be implemented. The effective risk communication requires the co-operation between organizations, clear and coordinated messages, and the engagement of speakers with good community credibility.
Momin, McNaughton et al., 2018 [83]	USA: Illinois, Minnesota, NorthCarolina	86 realtors	Qualitative study with 12 focus groups. To determine radon-related knowledge, attitudes, and practices among realtors to inform cancer control activities at local and state levels.	Realtors reported obtaining information on radon in similar ways, being aware of radon and its characteristics and dealing with radon issues as a normal part of home sales. Differences in attitudes toward testing varied across states. Realtors in states with radon policies generally expressed more positive attitudes toward testing than those in states without policies.

Table 1. *Cont.*

Authors, Year	Study Area	Population Characteristics	Study Design Objectives	Results
Neri, McNaughton et al., 2018 [74]	USA: Illinois, Minnesota, NorthCarolina, Ohio.	995 homebuyers	Questionnaire. To measure radon knowledge in diverse populations, with varying radon-related laws, to inform radon-related cancer control practices and activities.	Education is positively associated with home testing for radon. Partnering with real estate agents to further radon education and testing efforts to reduce radon exposure and lung cancer risk.
Ou, Ramsay et al., 2018 [77]	USA, Utah	494 individuals	Telephone survey. To identify patterns in radon awareness and testing.	People 55 years or older and living in rural counties were the least likely to identify radon as a risk factor for lung cancer. Radon testing and meaningful awareness of radon's link to lung cancer are low in Utah. Support is needed to improve radon education, awareness, and testing throughout the state.
Siza, Morrison et al., 2018 [80]	USA, Alabama	192 individuals	Questionnaire. To conduct a community assessment to obtain a better understanding of the current health-related needs of a community.	Identified gaps in exposure prevention and mitigation, including low lead and radon testing rates and a high prevalence of indoor smoking, were shared with the local health department, and recommendations for timely interventions and policy guidance (e.g., targeted education campaigns and smoking cessation programs) were presented.
Butler, Rayens et al., 2017 [54]	USA, Kentucky	515 homeowners	Descriptive correlational design. To examine the association of smoking in the home with lung cancer worry, perceived risk and synergistic risk, controlling for sociodemographic family history of lung cancer, and health-related self-concept.	Homeowners with smoking in the home, less education, and a family history of lung cancer had greater lung cancer worry and perceived lung cancer risk. Lung cancer risk reduction interventions with vulnerable populations are needed. Nurses are in a unique position to target high-risk populations and identify opportunities to create teachable moments to reduce environmental risks of radon and tobacco smoke exposure.
Lee, Yang et al., 2017 [69]	Korea	633 households	Questionnaire and measurement of indoor radon level. To (i) assess the degrees of exposure by various home types in which people generally have more exposure and spend more time, (ii) calculate the annual effective dose and risk in accordance with the exposure time and levels, and (iii) assess the awareness of radon of the residents of homes through a survey.	Residents of detached houses exceeded the average dose of 1.0 mSv/y, and homemakers who had long residence times were exposed to 6.9 mSv/y. 2. Residents of detached houses have a high risk of lung cancer, with 6.5 people in every 1000 at risk of developing lung cancer. Awareness level of Rn sources and indoor contamination was very low. Promoting habits reducing Rn exposure and educating about source, exposure, and ventilation are important.

Table 1. *Cont.*

Authors, Year	Study Area	Population Characteristics	Study Design Objectives	Results
Petrescu and Petrescu, 2017 [57]	Romania	229 individuals	Questionnaire. To assess and report, the perceptions, knowledge, and behaviors related to residential radon, in order to contribute to the creation of a healthier living environment.	Study results showed that most participants did not perceive the risk generated by radon exposure as significant to their health. The study shows that in Romania, increasing awareness, through the provision of valid information, should be a major objective of strategies to reduce radon exposure.
Huntington-Moskos, Rayens et al., 2016 [51]	USA, Kentucky	556 adults recruited at an academic medical center	Questionnaire. To determine whether having minor children was associated with the teachable moment constructs of lung cancer worry, perceived risk, health-related self-concept, and synergistic risk.	The presence of children in the home was not a significant predictor of any construct needed to create a teachable moment for lung cancer prevention. There is a critical need to raise parental awareness on child health inequities related to the home exposure to radon and second-hand smoke.
Rajaratnam and Sowmiya, 2016 [68]	India, Tamil Nadu	100 students	Questionnaire in English consisting of 20 items. To determine the awareness about indoor air pollution in young undergraduate medical students.	The students correctly answered the majority of the items. Regarding radon, it was asked if the decay of radium in the soil subjacent to a house was the main source of indoor air pollution with radon, and only 19% gave the correct answer.
Evans, Bodmer et al., 2015 [79]	USA, Vermont	169 subjects in 6 locations and 24 experts	Questionnaire. To gain an appreciation for current knowledge and perceptions, which exist on ionizing radiation (radon is one of those risks).	8% of respondents from the general population expressed having confidence in their knowledge of ionizing radiation, indicating a great need for additional public education; experts demonstrated a higher knowledge base regarding ionizing radiation than the general population.
Jones, 2015 [78]	USA, Colorado	230 individuals	Questionnaire via postal service. To gather feedback from participants in four radon education outreach venues: live class, distance education class, education booths at local events, and one-on-one consultation.	Participants were generally unknowledgeable about the hazards of radon exposure before the class but were knowledgeable following the class. Radon outreach programming will continue to be an important topic for many residents.
Nursan, Müge et al., 2014 [66]	Turkey, Sakarya province	362 individuals	Questionnaire. To assess the knowledge and perception of parents of high school students about the health effects of environmental hazards.	Of the participants, 98.6% knew that smoking was a health risk, but exposure to radon gas was not so prevalent (n = 194; 53.6%). There is a necessity to inform the public about lesser known but significant environmental risks such as radon gas and noise exposure, which may cause health problems.

Table 1. *Cont.*

Authors, Year	Study Area	Population Characteristics	Study Design Objectives	Results
Hahn, Rayens et al., 2014 [52]	USA, Kentucky	50 individuals	Administration home radon and SHS kits and baseline surveys. To assess the feasibility and impact of a brief home screening and environmental feedback intervention to reduce radon and SHS (FRESH Project).	Most of the participants (76%) returned the radon test kits; 48% returned SHS kits. Of the returned radon test kits, 26% were >148 Bq m^{-3}. Of the returned SHS kits, 38% had nicotine >0.1 $\mu g/m^3$. Of those with high radon, more than half contacted a mitigation specialist or planned contact. Of those with positive air nicotine, 75% adopted smoke-free homes. A significant increase occurred in perceived risk for lung cancer and synergistic risk perception after FRESH.
Hazar, Karbakhsh et al., 2014 [67]	Iran, Tehran	462 health care providers	Self-administered questionnaire. To assess (i) perceived risk of radon, knowledge and willingness to test, and willingness to pay for radon test, (ii) asked participants to rank their concerns about seven health risks: earthquake, radon, air pollution, exposure to microwave oven, food poisoning, solar radiation, and exposure to tobacco smoke.	About 67% had heard about radon before this study, and of these, 88.5% could correctly denote it as a radioactive gas. In addition, 83.5% of participants recognized it as being hazardous, and 34.5% identified lung cancer as the main health outcome of exposure to radon. Overall, 33% of 310 subjects had "knowledgeable awareness". They ranked the risk of exposure to indoor radon as being of the least importance, even after concern about food poisoning.
Rinker, Hahn et al., 2014 [50]	USA, Kentucky	129 homeowners	Questionnaire. To assess whether perceived severity, perceived susceptibility, synergistic risk perception, social influence, and smoking status are associated with the intention to test for radon.	Perceived severity, social influence, and education level were positively associated with radon testing intentions. On the contrary, current smoking was related to testing intentions. Synergistic risk perception was associated with higher perceived severity.
Clifford, Hevey et al., 2012 [30]	Ireland: Kerry, Castleisland	106 individuals	Questionnaire. To investigate the knowledge and attitudes of residents towards radon, a high radon area, following the discovery of a house with high radon levels.	People do not test their home because they believe their home does not have a problem. Optimistic bias was thought to play a role here. The subjective norm component was found to have a significant independent contribution in the variation in intentions to measure homes for radon.
Cinar, Altun et al., 2011 [64]	Turkey: region of Kocaeli	278 students	Questionnaire. To assess knowledge and attitudes on health effects of environmental risk of university students in an industrial city.	The lowest rate of correct answers (30.1%) was obtained with the question "residential exposure to radon gas is a risk factor for lung cancer". School education on significant environmental risks is extremely needed for these university students.

Table 1. *Cont.*

Authors, Year	Study Area	Population Characteristics	Study Design Objectives	Results
Fojtikova and Rovenska, 2011 [56]	Czech Republic	Two groups of respondents	In-depth interviews and focus groups with two groups of respondents—high radon concentration at home and building their house or plan to buy or build. To understand if a health marketing approach can be applied to promote the reduction of radon risk.	After a qualitative survey has been evaluated, an easy marketing action for promoting radon remediation in the Czech Republic was prepared. When realizing this plan, the number of homeowners applying for the remediation increased. It has been shown that the marketing approach can be helpful in radon risk management.
Poortinga, Bronstering et al., 2011 [65]	UK: England and Wales	1578 residents	Questionnaire/to examine whether (i) people's radon-related awareness, perceptions, and behavior vary according to the likelihood of exposure to radon, and (ii) a locally directed radon awareness and testing campaign has had an effect on people's radon-related awareness, perceptions, and behavior.	Awareness of radon is generally high in radon-affected areas. The radon roll-out program appears to have been effective in raising radon awareness and testing. As expected, residents of participating local authorities had higher levels of radon awareness and were more than twice as likely to have tested their homes for radon as residents of nonparticipating local authorities.
Downs, Ross et al., 2010 [84]	USA, Massachusetts	Residents of 14 homes	Community-based participatory research: residents and researchers tested fourteen homes. To pilot participatory testing and reporting that combined relatively simple tests with actionable reporting to empower residents.	Moderate–high success overall based on process and outcome criteria. The conflict burden may be attributable less to generic university–community differences in interests/culture and more to territoriality and interpersonal issues. Future work should fund the active participation of a few motivated residents as representatives of the target population.

4. Discussion

4.1. Summary of the Main Findings

In this literature review, the conceptual dimensions of risk perception and their increasing complexity were analyzed: understanding and awareness; perception of risk; communication of risk; willingness to perform radon monitoring tests; implementation of remediation actions. When there is no specific knowledge, the results show that knowledge of the radon risk is low or very low. In high-risk areas, information is often available but does not reach the target population because it is difficult to understand or disseminated through channels not used by the public. The perception of radon risk acted positively on the willingness to become active and engage when social or knowledge networks were activated, specific instruments were provided to measure radon, or the health of fragile individuals, such as children, needed to be protected. It was observed that older men in high occupations were the most likely to delay action, while younger men, women, and parents were most concerned about radon risk. Therefore, cognitive and emotional components of risk perception should be considered to understand protective behaviors and differences in age, ethnicity, and occupation type. The association between the perception of health risk and the intention to test for home exposure appeared clearly in several studies, particularly when the level of education was higher and social influences existed. The quantitative assessment of the association between knowledge/awareness/perception and actions such as radon testing and remediation was explored, and several studies showed positive associations, providing interesting elements for evaluating interventions. Economic and ethnic factors were associated with risk awareness and perception and therefore cannot be neglected. Furthermore, it has been reported that when the level of knowledge is rather high, optimistic prejudices may intervene, awareness may decrease, and the social dimension (what others do) becomes important. Among the actors who can influence radon risk knowledge and prevention, house sellers can be multipliers of available information, while health personnel were found to be poorly informed and needed training and support to play an active role. The synergistic risk of cigarette smoking associated with radon increases risk perception and protective behaviors, both personal and toward more fragile people such as children.

To summarize, it can be observed that the perception of radon risk is low, especially when compared with other environmental risks, and there are many factors that influence it: social, economic, emotional, and psychological characteristics that are analyzed to find the appropriate keys in the various contexts to make prevention actions effective, directly involving influential actors and the general population in communication actions, especially in areas at greater risk of domestic exposure to radon.

In this review of forty selected studies (2010–2021), the topic of risk communication was explored to capture methods and strategies to increase public awareness and willingness to improve the situation within buildings [57,59,69,72,76]. Some studies could be included in a citizen science paradigm [59–62,84]. Most of the studies contained recommendations addressed to different actors responsible for specific activities in policy and governance processes [80,81,84]. Cancer risk prevention was a productive context for producing information and generating awareness on radon risk [54–56,74,75,78,87].

4.2. Relationship between This Review and Previous Studies

Considering the relevance of uncertainty and perception in risk communication and management, radon appears as a paradigmatic and very peculiar example, as it is characterized by:

(a) Low widespread knowledge of the existence of this risk factor and low risk perception;
(b) Low epistemic uncertainty because there is a high level of knowledge about the physics of radon, the pathway from the environment to the human body, the mechanism of radiation damage, and the knowledge that it is a certain human carcinogen for lungs;

(c) High casual uncertainty because the possible damage, lung cancer, recognizes many other certain causes, such as smoking, exposure to arsenic, air pollution, and alcohol and has a very long latency time during which damage may or may not occur.

There is a generic perception on the pervasiveness of uncertainty, which often does not distinguish between random uncertainty which, as the name implies, refers to the intrinsic randomness of the phenomenon under investigation, and epistemic uncertainty, which mainly concerns the lack of knowledge [89]. The intrinsic component is more easily understood because it depends on previous experience. The case of radon is very special because, in the face of established and undisputed knowledge about carcinogenicity and lung cancer risk, the source and how exposure occurs are largely ignored. The conceptualization about communicating uncertainty is part of different disciplinary fields, for example, the biological field [90], the decision analysis field, and the management of natural resources field [91]. According to Regan, the sources of epistemic uncertainty can be classified into six types: measurement errors; systematic errors; modeling errors; subjective judgment; natural variation; intrinsic randomness [89]. The observations that the epistemic uncertainty is directly linked to decision making and it is the subject of daily confrontation for everyone, and in particular for scientists, seems particularly relevant in the case of radon. Marthe van der Bles and colleagues [92] point out well how, in the approach to uncertainty, communication is based on two levels of uncertainty: the direct one, which touches on specific facts, numbers, or patterns, and the indirect one, which questions the very quality of our knowledge. Their observation, that often those who have to communicate a scientific result or make public decisions are convinced that the clarification of uncertainties can produce negative consequences [92], is relevant when dealing with radon. The psychological dimension occupies a prominent place, since it is not just a question of finding technically correct approaches but also of interpreting the effects of communicating uncertainty to the listener [93].

The health of people and populations living in areas with high radon presence can certainly be improved by reducing exposure to radon itself and other risk factors (synergistic factors). It is important to increase and strengthen awareness actions using the scientific knowledge gained, constantly monitoring progress to strengthen further actions, as these programs should be planned for the long term, with central coordination and continuous evaluation [94].

Citizen science experiences, where individuals and/or a community contribute with new data and original perspectives to scientific studies developed on behalf of the collectivity [88], were limited in the studies included in this review [59–62,84]. However, this involvement, often directly required by communities in high-risk areas, is crucial to enhance community self-sufficiency, responsibility, and the quality of preventive actions [95]; for those reasons, it could be important to solicit the direct involvement of citizens in radon prevention campaigns. Citizen science is increasingly used in the field of radiation protection, as shown in the ENGAGE project promoted by the EU [96], and regarding radon, it was examined by the article of Martell and colleagues, which considered some of the studies included in the present systematic review [97]. The relevant elements that emerge from the analysis of eight citizen science initiatives, which basically made it possible to collect data on the presence of radon, are collected in 10 points. Among the most significant are the production of original scientific results, the benefits to citizens in terms of knowledge, personal, and social control, and the benefits to researchers in terms of knowledge, networks of relationships, and personal satisfaction for all involved [97].

4.3. Limitations and Strengths

This is the first systematic review to investigate the relationship between radon exposure and radon risk perception, communication, and possible mitigation activities carried out to provide useful information for the development of future research focusing on radon risk communication, dissemination, and governance.

In writing this paper, the PRISMA guidelines were followed, one of the most appropriate tools for conducting systematic reviews. Although three different databases were searched to identify as many studies as possible over a recent but not short time span, an incompleteness of articles, particularly in languages other than English or published in grey literature, cannot be ruled out.

As a strength, it must be underlined that all the steps of the review process, from abstract choice to the reading of all papers selected, were performed by four of the authors.

4.4. Conclusions: Theory, Practice, and Policy Formulation

Radon risk is in a complex dimension, with cognitive and emotional spheres closely interlinked. Understanding the topics can affect values, affectivity, trust, and behavior. This has implications on decision-making processes, for example, on the public health measures to be taken. According to van der Bles and colleagues, studies on the emotional and psychological effects of uncertainty are currently insufficient, and one should not stop at the conventional view that "people only want certainty" but explore the notion of uncertainty in order to assess its type and characteristics [92]. Information will act as a driver of behavior if it can overcome the many biases individuals have towards processing risk information. When risks are threatened, some cognitive and emotional mechanisms drive people to action, others to inaction. The threat of radon can easily be downplayed to justify inaction. Risk perception is subject to numerous unconscious, cognitive, and emotional biases that influence how radon information is processed; these biases act to minimize our perception of risk. Given these challenges, it is not surprising that radon threats fail to promote the appropriate precautionary behavior. Even when there is radon awareness, there tends to be apathy rather than a sense of urgency [25]. There are no immediate indicators of threat: there are no obvious "dead bodies", and radon-related lung cancer occurs in the distant future [98].

Risk communication can play a key role in making risk prevention possible by reducing exposure, especially when integrated into citizen science experiences, where citizens directly take the initiative and assume responsibility for producing the knowledge and dealing with the management of results and prevention actions together with the competent authorities. Health communication that refers to a threat tends to evoke fear and increase the perception of the severity of the threat. To properly target communication, it is strategic to know people's knowledge and awareness, their perception of the radon risk, and their readiness for action (risk monitoring and mitigation measures). Risk perception is linked to emotions and reason, which creates rational behavior and can vary according to people's status, background, education, biology, etc. [99].

A multidisciplinary approach, involving constant collaboration with experts in the field of psychology, has been advocated as essential for solving the problems associated with radon mitigation [27]. A key challenge for risk awareness programs is to inform the target audience in a way that does not create apathy, complacency, or overconfidence, without creating undue stress or alarmism [26] and supporting citizen participation. Developing those programs, it is also crucial to use quantitative methods to evaluate the results of the actions taken and the association between risk awareness and willingness to take preventive action. Moreover, future research and action should use the most effective methods to minimize the risk of selection bias by obtaining results that are representative of the entire population. Research for the implementation of evidence-based radon communication programs should be developed and strengthened, building on the work that has been performed and ongoing developments, in particular in the European Union through the implementation of the EU Directive 2013/59. National radon action programs should support multidisciplinary scientific collaboration in the field of risk perception, together with culturally appropriate communication strategies, as indicated in The Potsdam Radon Communication Manifesto [34,94].

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