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Research Article

Indoor Air Quality: Predicting and Comparing Protective Behaviors in Germany and Portugal

Inês Veiga,[1] **Mijail Naranjo-Zolotov**,[1] **Ricardo Martins**,[1] **Tiago Oliveira**,[1] **and Stylianos Karatzas**[2]

[1]*NOVA Information Management School (NOVA IMS), Universidade Nova de Lisboa, Campus de Campolide, 1070-312 Lisboa, Portugal*
[2]*Department of Civil Engineering, School of Engineering, University of Patras, 26500 Patras, Greece*

Correspondence should be addressed to Inês Veiga; iveiga@novaims.unl.pt

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This study investigates the adoption of indoor air quality (IAQ) management technologies in Germany and Portugal, focusing on the common and differentiating factors influencing individuals' motivations and the perceived health impacts of these technologies. Utilizing a model based on the protection motivation theory, we surveyed 800 participants (400 from each country) to understand how their perceptions of the risks associated with poor IAQ and their evaluations of the effectiveness and costs of technologies like air purifiers and sensors drive the adoption intention of these technologies and well-being of individuals. To estimate the complex relationships in our model, we employed partial least squares structural equation modeling (PLS-SEM). Our model explains nearly 50% of the variance in well-being for both countries. The results revealed significant differences in the factors driving technology adoption: Germans are primarily motivated by individual efficacy and personal responsibility with the people close to them. Regarding the similarities, participants from both countries value the technology's effectiveness in improving IAQ and do not see being vulnerable to health issues derived from poor IAQ as a motivator. These insights highlight the need for strategies that are tailored to specific cultural and national contexts to promote the adoption of IAQ management technologies, aiming to enhance IAQ and public health outcomes.

Keywords: cross-country; indoor air quality; PLS-SEM; protection motivation theory; technology adoption; well-being

1. Introduction

Indoor air quality (IAQ) is a major concern as the level of contaminants, such as fine particulate matter (PM 2.5), volatile organic compounds (VOCs), and carbon dioxide (CO2) surpass building standards [1]. This stands out as a major environmental and public health concern [2, 3], as European citizens spend approximately 90% of their time indoors [4] and inadequate IAQ ultimately leads to the loss of healthy years of life and premature deaths [5, 6]. For instance, in 2021 alone, an estimated 253,000 people in Europe died prematurely due to exposure to fine PM 2.5 [7]. Furthermore, there are other consequences resulting from poor IAQ, such as allergies, respiratory symptoms, reduced performance, and sleep quality [8, 9].

The health and well-being of occupants are directly impacted by poor IAQ; thus, there is a necessity for initiatives to manage IAQ within living spaces to mitigate the adverse outcomes linked to poor IAQ [10, 11]. Technology has shown promising results in detecting, monitoring, and improving pollutant levels regarding IAQ. Specifically, IAQ management technologies can include sensors; wearables and portable technologies [12, 13]; heating, ventilation, and air conditioning systems (HVAC); air filtration units; and air purifiers [14, 15]. For instance, air filtration units and air purifiers in diverse indoor environments, such as vehicles, residences, and classrooms have proved to be effective in reducing PM [3, 16]. Similarly, portable air purifiers have shown an effective short-term decrease in PM [17, 18]. Furthermore, air filters in HVAC systems play a crucial role in protecting individuals against viruses and bacteria, which becomes especially important in epidemic infections [19, 20].

In previous studies, the adoption of IAQ management technologies promoted users' behavior change. For instance, in two studies where individuals tried an air quality sensor, there was a significant increase in participants' air pollution knowledge regarding health consequences, pollution sources, and mitigation strategies, with individuals feeling more confident and empowered to take more action to mitigate indoor air pollutants [21, 22]. However, most studies focus on directly testing the interventions to understand their efficacy in predicting pollutant levels [23, 24], monitoring pollutants [25, 26], and their impact on improving users' health or the environment [14, 27], and a limited body of research employs a behavioral approach to address this matter [28, 29]. Therefore, there is a lack of studies that focus on the drivers of adoption behavior. Effectively addressing this issue requires understanding the factors motivating individuals' protective behaviors regarding the safeguard against the adverse effects of poor IAQ to support behavior change and promote users' technology adoption.

Previous studies that compared health technology adoption in different countries yielded relevant insights, for instance, the acceptance of wearable technologies between China and Switzerland [30]. Therefore, it is imperative to test the differences when conducting a study with a sample from more than one country within an apparently similar context, as all countries have their own culture and different perceptions of reality [31]. Thus, one might not get an accurate or complete story if one only acknowledges the big picture without considering the differences.

Germany and Portugal are characterized by distinct health profiles, with Germans exhibiting a more positive self-perceived health [32], greater healthy life years at birth [33], and a stronger propensity to do physical exercise [34, 35]. Furthermore, there are also significant cultural differences between both countries [31]. Germany stands out as a strongly individualistic society, emphasizing close family ties and taking care of direct family, prioritizing self-actualization, independence, and personal responsibility [31, 36]. In comparison, Portugal is more moderate when it comes to these notions. Furthermore, in Portugal, there is a strong concern for establishing absolute truths, respect for traditions, and a preference for quick results over long-term planning. In Germany, the opposite is true [31, 36]. Therefore, we expect to uncover significant differences between the two countries.

To the best of our knowledge, there are no studies on the adoption of IAQ management technologies with a cross-country approach. Thus, to further contribute to the body of knowledge, we aim to uncover what motivates individuals' protective behaviors and the intention to adopt IAQ management technologies with a cross-country perspective, by comparing two European countries, namely, Germany and Portugal. We also aim to uncover if individuals perceive these behaviors to have a positive impact on their health.

2. Research Model and Hypotheses

To understand the differences in protection motivation and adoption intention of IAQ management technologies, we draw upon a theory from the psychology field: the protection motivation theory (PMT) [37], which has been previously successfully employed to study individual behavior in the health context [38]. Besides, PMT has been empirically validated in various contexts, such as cybersecurity [39, 40], tourism [41, 42], and physical activity [43, 44]. Thus, it is a well-established theoretical framework for understanding how individuals perceive and respond to threats, ensuring a robust basis with a strong empirical foundation for analyzing behaviors related to IAQ management technologies. Furthermore, PMT's effectiveness in understanding health-related behaviors lends credibility to its application in studying IAQ management technologies. Given that IAQ directly impacts health, using PMT in this context is particularly relevant.

Furthermore, PMT offers a comprehensive model that explains how individuals assess and respond to threats, and it encompasses two core stages: threat appraisal and coping appraisal [37, 45]. This dual-stage approach allows for an examination of individuals' perceptions of threats posed by poor IAQ and their evaluations of potential coping mechanisms. More specifically, threat appraisal helps in understanding individuals' perceptions of the severity of IAQ-related threats and their vulnerability to these threats [46]. This insight is crucial for designing interventions that effectively communicate the risks associated with poor IAQ and motivate protective behaviors. Moreover, coping appraisal delves into how individuals evaluate the protective measure's costs and efficacy and their own self-efficacy in adopting the protective measure, such as adopting IAQ management technologies [47]. This helps in identifying motivators and barriers to adoption and designing tailored strategies.

Additionally, we approach the theory of basic individual values [48], adding the value of benevolence–caring as a moderator of the relationships between protection motivation and behavioral intention to explain variations on the impact of protection motivation on adoption intention. The value of benevolence–caring pertains to the notion of prioritizing the welfare of those within one's immediate close circle of family and friends, underscoring a commitment to their well-being rather than extending it to a broader context [48]. Finally, we introduce well-being as a dependent variable, which refers to the contribution of adopting protective measures to one's health, namely, having increased control over one's health [49]. Our model has nine hypotheses, with five of them having two variations (labeled a and b). Theoretical models with multiple hypotheses capture the complexity of the phenomena being studied, following a widely used approach for studying human behavior in relation to technology [50, 51]. Figure 1 illustrates our research model.

Starting with threat appraisal, individuals engage in a cognitive process to assess how severe they think the threat of having poor IAQ is. Thus, individuals with a high level

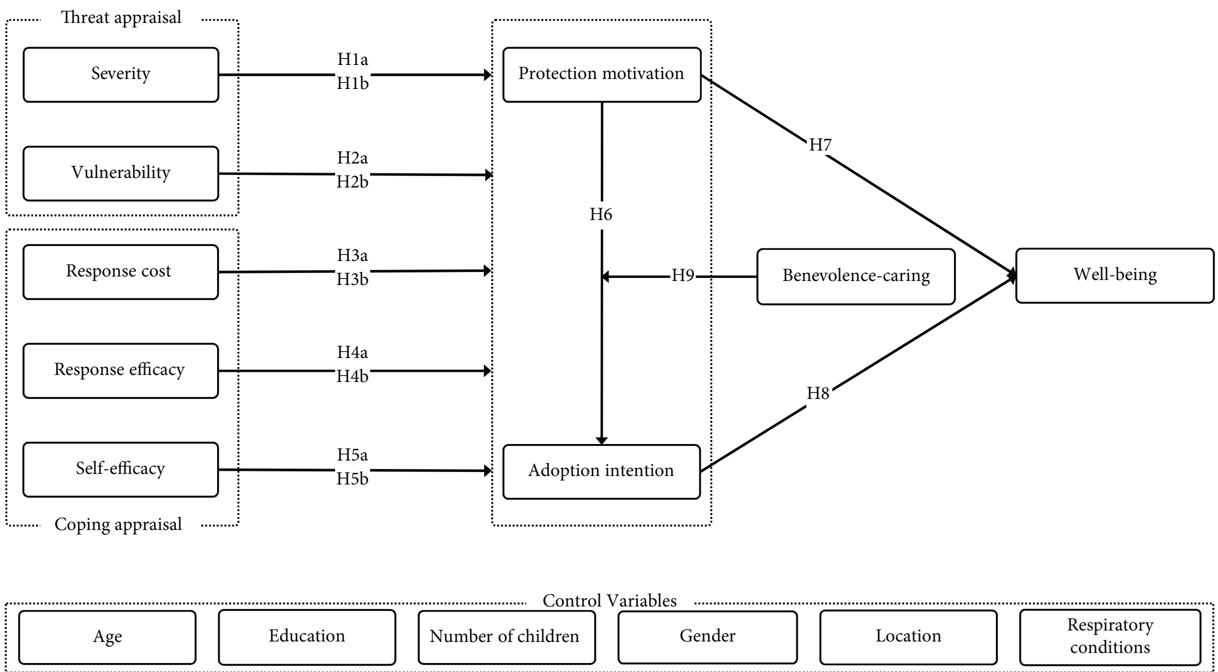

Figure 1: Research model.

of severity are substantially worried about poor IAQ and concerned with the IAQ levels. Therefore, severity plays a pivotal role in shaping an individual's perception of the seriousness of the threat, and thus, it influences the subsequent responses [52, 53]. Therefore, we hypothesize the following:

H1a: Severity will positively influence protection motivation.

H1b: Severity will positively influence IAQ management technology's adoption intention.

Vulnerability is the perception of how vulnerable one is to the consequences of poor IAQ. It entails contemplating the chances of falling victim to the threat and the degree to which one is exposed to its potential consequences [47]. This dimension delves into concerns related to potential health issues that may arise due to IAQ, encompassing worries about developing IAQ–related health problems and apprehensions about undiagnosed health issues resulting from poor IAQ. Thus, vulnerability can motivate the adoption of protective measures [38, 53]. Therefore, we hypothesize the following:

H2a: Vulnerability will positively influence protection motivation.

H2b: Vulnerability will positively influence IAQ management technology's adoption intention.

Response cost refers to any associated costs, such as the monetary, personal, time-related, or required effort [47], that individuals associate with using IAQ management technologies. When individuals perceive IAQ management technologies as inconvenient, time-consuming, requiring significant effort or expense, or involving the need to develop new habits, their likelihood of engaging in protective behaviors is reduced. Hence, we hypothesize the following:

H3a: Response costs will negatively impact protection motivation.

H3b: Response costs will negatively impact IAQ management technology's adoption intention.

Response efficacy embodies the conviction that adopting the chosen protective action has the potential to effectively counteract the threat in question, reinforcing their motivation to engage in these actions to protect one's health [47]. Therefore, individuals who perceive the protective measures as highly effective are more likely to adopt protective behaviors and IAQ management technologies. Hence, we hypothesize the following:

H4a: Response efficacy will positively influence protection motivation.

H4b: Response efficacy will positively influence IAQ management technology's adoption intention.

Self-efficacy is a foundational element of coping appraisal, encompassing an individual's perception of their own capability to effectively use IAQ management technologies. It reflects the person's belief in their capacity to carry out actions or behaviors against the identified threat [47]. Therefore, we hypothesize that individuals who feel more capable of using these technologies will be more motivated to protect themselves against poor IAQ and want to adopt them to manage IAQ [38, 53].

H5a: Self-efficacy will positively influence protection motivation.

H5b: Self-efficacy will positively influence IAQ management technology's adoption intention.

Protection motivation delves into an individual's intention to engage in recommended coping behaviors aimed at mitigating the identified threat. These adaptive strategies empower individuals to take actionable steps to protect themselves against the perceived threat [54]. Therefore, individuals who are motivated to protect themselves against the threat of poor IAQ will be more likely to intend to adopt IAQ management technologies:

H6: Protection motivation will positively impact IAQ management technologies adoption intention.

The concept of well-being was first addressed in the context of health-oriented smart homes, which help improve medical assistance and patients' lives, and it conveys the idea of how using these technologies can empower individuals regarding their health [49]. Therefore, we hypothesize that users who protect themselves against poor IAQ will perceive a greater positive impact on their health:

H7: Protection motivation positively impacts well-being.

H8: IAQ management technology's adoption intention positively impacts well-being.

We suggest that individuals motivated to adopt protective behaviors against poor IAQ are more inclined to adopt IAQ management technologies. However, we further extend this notion by hypothesizing that individuals with higher levels of benevolence–caring may perceive a heightened responsibility to ensure a healthy indoor environment for their loved ones [48], thus intensifying their intention to adopt IAQ management technologies as a means of protection.

H9: Benevolence–caring will positively moderate the relationship between protection motivation and behavioral intention.

3. Methods

3.1. Construction of the Questionnaire. The items measuring our variables were based on the works of Laugesen and Hassanein [47] and Zheng, Lou, and Ritchie [54] and tailored to our study's context. The items were measured using a 7-point Likert scale, ranging from "*strongly disagree*" (1) to "*strongly agree*" (7), and were translated from English into Portuguese and German. These translations were rigorously reviewed by native speakers of each language and subsequently back translated to ensure accuracy [55]. In addition, our questionnaire captured self–reported sociodemographic information, including age, gender, education level, and respiratory conditions. The items are available in the supplementary material, Table I.

3.2. Data Collection. Prior to data collection, the questionnaire received approval from the NOVA IMS Ethics Committee, confirming compliance with European regulations. Informed consent was obtained from all participants before their involvement in the study. Additionally, a pilot study was conducted with 55 respondents to ensure the survey's clarity. Subsequently, the final questionnaires were administered online, over a 2-week period, at the end of July 2023, by a subcontracted company specialized in data collection.

The target population for this study consisted of potential adopters of IAQ management technologies above 18 years old from Germany and Portugal. Potential adopters can include any individuals likely to embrace and start using a new technology. The participants were randomly recruited online and the only exclusion criteria was age (below 18). To calculate the sample's appropriate size, an infinite population size model was adopted, considering the pessimistic hypothesis ($\boldsymbol{p} = \mathbf{0.50}$) [56], which gives us a minimum required sample size of 385. Consequently, 400 complete survey responses per country comply with the infinite population size model.

The sampling technique employed in this study combines elements of quota sampling and random sampling to ensure both representativeness and randomness in the sample selection process [57]. Quota sampling involves establishing quotas based on key demographic characteristics, to mirror the population's distribution. However, within each quota, individuals were selected randomly. This dual approach allows for the control of important demographic factors while maintaining randomness and avoiding bias in the selection process. Quotas, as detailed in Table 1, were established based on age and gender to ensure similarities between the sample and population of each country. There are no statistically significant differences (in Table 1, $\boldsymbol{Z}$-value < 1.645) between the age and gender of the population and sample for both countries based on the proportion test.

3.3. Data Analysis. To analyze the relationships in our research model and ensure its validity, we employed the partial least squares structural equation modeling (PLS-SEM) method. This choice was motivated by the complexity of the model, which included numerous constructs and indicators [58]. Furthermore, it is indicated for exploratory research [58]. First, we used the software SmartPLS 4 to assess the measurement model to evaluate construct reliability, indicator reliability, convergent validity, and discriminant validity and interpret the structural model to understand the relationships within the research model and validate them.

Furthermore, PLS-SEM with bootstrapping allows us to assess the significance of path coefficients and compare them between the two countries. Bootstrapping is a nonparametric resampling technique that generates numerous subsamples from the original data, in our case, 5000 iterations. This iterative process allows us to estimate the precision of the PLS-SEM estimates by constructing confidence intervals around the path coefficients, thereby assessing their stability and significance [59]. The use of bootstrapping mitigates sampling error, ensuring consistency and reliability in our results, which is critical for making robust statistical inferences, especially when comparing different groups, such as the countries in our study [59].

4. Results

4.1. Sample Description. We obtained a total of 800 valid and complete responses, 400 responses per country (Germany and Portugal). In the Portuguese sample, 34% have a high school diploma, and 38% hold a bachelor's degree. In the German sample, 42% have an apprenticeship, and 29% earned a bachelor's degree. Among the Portuguese and German samples, we can verify that most individuals have no respiratory conditions (85% and 80%, respectively) and live in the city center (47% and 50%, respectively). The data is available in Table S2.

Table 1: Population and sample quotas by age and gender.

	Population		Sample ($n = 400$ by country)		Z -value (proportion-test)	
	Germany	Portugal	Germany	Portugal	Germany	Portugal
Age (years)						
< 36	37.8%	35.1%	36.5%	36.8%	−0.56	0.71
36–50	18.5%	21.4%	17.5%	24.5%	−0.50	1.49
> 50	43.7%	43.5%	46.0%	40.0%	0.94	−1.41
Gender						
Male	49.3%	47.2%	49.0%	47.0%	−0.12	−0.08
Female	50.7%	52.8%	51.0%	53.0%	0.12	0.08

Table 2: Total sample descriptive statistics: mean, standard deviation, Cronbach's alpha, composite reliability, average variance extracted, correlations, and the square root of average variance extracted.

Variable	Mean (SD)	CA	CR	AVE	Sev	Vul	RC	RE	SE	PM	AI	HWB	BC
Severity (Sev)	4.24 (1.89)	0.94	0.94	0.81	*0.90*								
Vulnerability (Vul)	4.91 (1.65)	0.95	0.95	0.86	0.72	*0.93*							
Response cost (RC)	4.76 (1.74)	0.82	0.83	0.63	0.30	0.28	*0.79*						
Response efficacy (RE)	5.56 (1.33)	0.91	0.92	0.79	0.40	0.55	0.05	*0.89*					
Self-efficacy (SE)	5.35 (1.38)	0.85	0.85	0.69	0.38	0.42	0.15	0.70	*0.83*				
Protection motivation (PM)	4.69 (1.67)	0.93	0.93	0.82	0.58	0.47	0.20	0.47	0.42	*0.90*			
Adoption intention (AI)	4.70 (1.81)	0.96	0.96	0.93	0.56	0.57	0.08	0.60	0.53	0.57	*0.97*		
Well-being (WB)	5.49 (1.40)	0.95	0.95	0.87	0.42	0.52	0.00	0.76	0.59	0.45	0.65	*0.93*	
Benevolence–caring (BC)	6.16 (1.09)	0.93	0.95	0.87	0.06	0.20	0.02	0.41	0.33	0.16	0.21	0.45	*0.93*

Note: Italic is the square root of the average variance extracted.
Abbreviations: AVE = average variance extracted. CA = Cronbach's alpha. CR = composite reliability. SD = standard deviation.

4.2. Measurement Model. We conducted a comprehensive evaluation of multiple aspects to assess the quality of our reflective measurement model. We evaluated internal consistency utilizing composite reliability (CR), which establishes the reliability of our constructs [59]. Furthermore, we assessed convergent validity with the indicators' outer loadings and the average variance extracted (AVE). In Table 2, all constructs exhibit a CR exceeding the threshold of 0.7 and an AVE value exceeding the threshold of 0.50, and all the diagonal elements representing the squared root of AVE surpass the values of the correlations between the constructs [59]. The indicators within each construct are dependable and collectively share a substantial amount of common variance [59]. We also evaluated discriminant validity, where we looked at the cross-loadings and the heterotrait–monotrait (HTMT) ratio of correlations. The corresponding tables are available in Table S3 and Table S4. We can determine that all loadings are above 0.60, the recommended threshold for exploratory research [58], and they all display values higher than the cross-loadings [59]. Finally, all the diagonal values representing the HTMT are below the threshold value of 0.90 [58]. These figures confirm that our constructs are indeed distinct from one another and measure unique underlying concepts [59].

The results presented for the measurement model correspond to the calculations done with the overall sample. The measurement model was also evaluated for each country, and there were no identified issues or anomalies. Thus, we can proceed to the evaluation of the structural model.

4.3. Structural Model. We can confirm from the country-specific R^2 value that there is a good explanatory value for all our target variables. However, in the case of Germany, there is an overall tendency for a stronger effect over our target variables, especially regarding the adoption intention and protection motivation, where our model explains 69.8% and 58.5% of the variance for Germany. Whereas for Portugal, our model only explains 53.2% of the variance in adoption intention and 30.2% in protection motivation. Figure 2 illustrates the structural model results for Germany and Portugal.

The results of our study support the use of PMT to explain the differences in the adoption of protective behaviors for the full sample, with only one rejected hypothesis, and for both countries. In Germany, 11 out of the 14 hypotheses were significant, whereas in Portugal, only 6 out of the 14 hypotheses proved to be statistically significant (see Table 3). In both countries, when individuals are deciding to cope with the threat of poor IAQ, response efficacy is important. However, self-efficacy is only important in the case of Germany.

Regarding threat appraisal, vulnerability does not predict our target variables for both countries. However, it is interesting to note that this is not the case when we consider the full sample. This is due to differences in sample size and the ability of the statistical methods used to detect effects. That is, a small effect size combined with a smaller sample size can result in statistically nonsignificant results [60]. However, when we combine the data from both countries, we increase the overall sample size and consistency

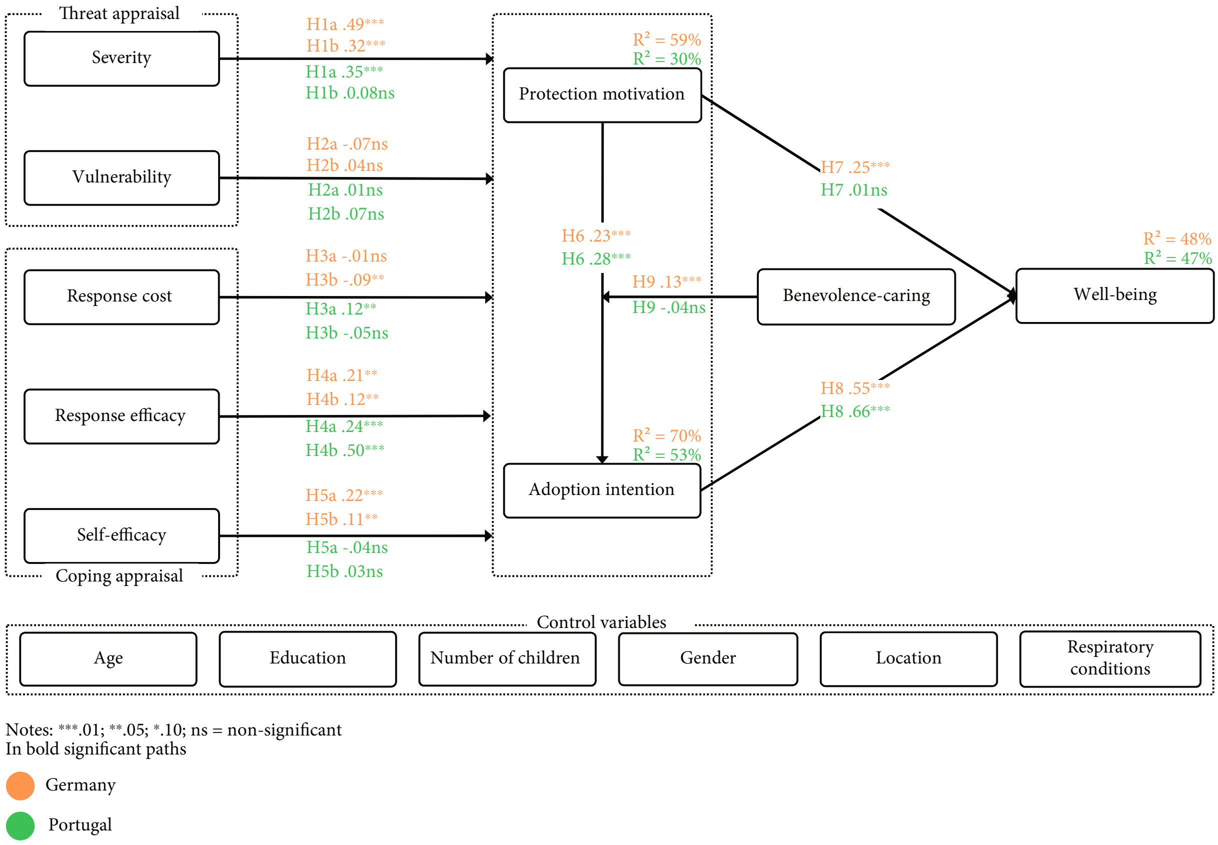

Figure 2: Structural model results for Germany (in orange) and Portugal (in green), with the significant paths in bold.

across the samples; thus, small effects become more likely to reach statistical significance (Germany's effect size = 0.00, Portugal's effect size = 0.00, and total sample's effect size = 0.02).

Moreover, for both countries, individuals who are already motivated to protect themselves against poor IAQ are more likely to adopt IAQ management technologies. However, benevolence–caring only functioned as a moderator for Germany. Finally, we also found that well-being is seen as an outcome of adopting IAQ management technologies for both countries.

4.4. Multigroup Analysis. We performed a PLS multigroup analysis, which builds on the PLS-SEM bootstrapping results [44], by subtracting Portugal's path coefficients from Germany's path coefficients to highlight the significant differences between the two groups (Germany vs. Portugal). There are significant differences between both groups regarding protection motivation in the impacts of response cost and age, which are only significant for Portugal, whereas self-efficacy is only significant for Germany. There are also significant differences in the predictors of adoption intention when it comes to the impacts of severity, benevolence–caring, and living location, which are only significant for Germany.

Additionally, the impact of response efficacy is relevant for both countries but significantly greater for Portugal. Lastly, age is also significant in both countries but considerably more important for Germany. Finally, when it comes to well-being, there are significant differences with age and protection motivation being important only for Germany and respiratory conditions being important only for Portugal. The differences between Germany and Portugal are detailed in Table 4.

5. Discussion

5.1. Theoretical Implications. Our research, emphasizing a cross-country perspective, unveils insights into the drivers behind protective behaviors against poor IAQ and the adoption of IAQ management technologies to promote behavior change [45]. In a world where IAQ is increasingly recognized as critical, our research delivers valuable and practical insights that can benefit fellow researchers and inform strategies and initiatives aimed at promoting healthier indoor environments and public health initiatives.

Starting with the target variable protection motivation, when evaluating coping strategies to mitigate the perceived threat of poor IAQ, self-efficacy is the most important factor for German individuals. This observation aligns with previous literature on the adoption of protective behaviors during the COVID-19 pandemic [52, 53] and protective behavior against smog [61]. In the case of Portugal, when it comes to coping appraisal, the most critical factor is response efficacy, followed by response cost. This finding aligns with prior research on the adoption of electronic personal health records [47]. Interestingly, self-efficacy does not exhibit a

Table 3: Hypothesis assessment for each country and the overall sample.

Hypotheses		Overall	Germany	Portugal
H1a	Severity→protection motivation (PM)	S	S	S
H1b	Severity→adoption intention (AI)	S	S	R
H2a	Vulnerability→protection motivation (PM)	R	R	R
H2b	Vulnerability→adoption intention (AI)	S	R	R
H3a	Response cost (RC)→protection motivation (PM)	S	R	S
H3b	Response cost (RC)→adoption intention (AI)	S	S	R
H4a	Response Efficacy (RE)→protection motivation (PM)	S	S	S
H4b	Response Efficacy (RE)→adoption intention (AI)	S	S	S
H5a	Self-efficacy→protection motivation (PM)	S	S	R
H5b	Self-efficacy→adoption intention (AI)	S	S	R
H6	Protection motivation (PM)→adoption intention (AI)	S	S	S
H7	Protection motivation (PM)→well-being (WB)	S	S	R
H8	Adoption intention (AI)→HWB	S	S	S
H9	Benevolence – caring × protection motivation (PM)→adoption intention (AI)	S	S	R

Abbreviations: R = rejected; S = supported.

significant impact in Portugal, contrary to our expectations and previous results related to protective behaviors against smog [28] and the COVID-19 pandemic [38, 62]. The significant difference between these two countries could be attributed to the cultural differences [31], as Germany is an individualistic society where personal autonomy and self-reliance are highly prized [36].

When individuals are appraising the threat before deciding to deal with it, for both countries, vulnerability has no impact. In contrast, severity has a significant impact in both countries. In fact, severity is the strongest predictor of protection motivation for both countries. The lack of impact of vulnerability over protection motivation, although it does not confirm our hypotheses, is in accordance with previous studies on protective behaviors during the COVID-19 pandemic [52, 62]. This aspect may be attributed to the fact that individuals, regardless of perceived personal vulnerability to the consequences of poor IAQ, still recognize poor IAQ as a severe threat and prioritize protection against it. This heightened awareness could be influenced by the fact that since the COVID-19 pandemic, people are more conscious about adopting protective behaviors out of a sense of responsibility and solidarity towards other people [63, 64].

Analyzing the factors influencing the intention of Portuguese individuals to adopt IAQ management technologies, our results highlight that only response efficacy, the most influential predictor in the model, and protection motivation proved to be significant. This aspect means that for Portuguese individuals to consider adopting these technologies, they must perceive them as effective in improving and managing the IAQ and contributing positively to their health. Similar findings have been reported in studies on the adoption of air purifiers [28]. Furthermore, individuals motivated to take measures to protect themselves against poor IAQ are more inclined to adopt IAQ management technologies. This finding aligns with the work of Zheng et al. [54], who found that protection motivation impacted travel behaviors after the COVID-19 pandemic.

For Germany, all variables in coping appraisal are significant predictors of adoption intention, aligning with findings in previous literature [28]. However, in threat appraisal, only severity, also identified as the strongest predictor, significantly influences the intention to adopt IAQ management technologies [28]. Moreover, in Germany, individuals who not only want to protect themselves against poor IAQ but are also committed to safeguarding the well-being of those dear to them are more likely to intend to adopt IAQ management technologies. Figure 3 illustrates that for those with high levels of benevolence–caring, the importance of protection motivation is higher to explain adoption intention. Conversely, protection motivation is less relevant to explain adoption intention for individuals who present low levels of benevolence–caring.

We observe noteworthy differences by examining the control variables outlined in Table 3. In Portugal, older individuals exhibit higher levels of protection motivation, aligning with prior research on protective behaviors against COVID-19 [65]. Regarding adoption intention, age significantly influences both countries, with younger individuals having higher levels of adoption intention, particularly pronounced in Germany. This finding is attributed to the tendency of younger generations to embrace new technologies more easily when compared to older generations [66], influencing their likelihood to change their approach in dealing with IAQ-related problems. Notably, in Germany, older individuals place greater value on having control over their health. As emphasized in prior studies, the young and the elderly might prioritize distinct variables when engaging with these types of technologies [67, 68].

In Germany, the location where individuals reside significantly influences adoption intention, with residents of more urban environments exhibiting higher levels of adoption intention. Conversely, in Portugal, individuals with respiratory conditions attribute greater importance to these technologies due to their potential to enhance health and provide increased control over well-being. This outcome

Table 4: Path coefficients for the full sample, by country (Germany and Portugal), and the differences between Germany and Portugal.

Variables		Dependent variable	Full sample	Germany	Portugal	Difference (Germany–Portugal)
Independent variables	Severity	Protection motivation	0.47***	0.49***	0.35***	0.14
	Vulnerability		−0.06	−0.07	0.01	−0.08
	Response cost		0.06**	−0.01	0.12**	−0.14*
	Response efficacy		0.24***	0.21***	0.24***	−0.03
	Self-efficacy		0.09*	0.22***	−0.04	0.26***
Control variables	Age		0.03	−0.04	0.13**	−0.17***
	Number of children		0.13***	0.13***	0.08	0.05
	Education		0.00	0.03	−0.01	0.03
	Gender		0.09*	0.05	0.13	−0.08
	Living location		−0.04	−0.01	−0.05	0.04
	Respiratory conditions		0.05	0.04	−0.03	0.06
Independent variables	Severity	Adoption intention	0.18***	0.32***	0.08	0.24***
	Vulnerability		0.14***	0.04	0.07	−0.03
	Response cost		−0.09***	−0.09**	−0.05	−0.04
	Response efficacy		0.24***	0.12**	0.50***	−0.38***
	Self-efficacy		0.12***	0.11**	0.03	0.07
	Protection motivation		0.20***	0.23***	0.28***	−0.05
	Benevolence–caring		0.07*	0.11**	−0.04	0.14**
	Benevolence − caring × protection motivation		0.09***	0.13***	−0.04	0.17***
Control variables	Age		−0.20***	−0.20***	−0.08*	−0.13**
	Number of children		0.11***	0.07**	0.06	0.01
	Education		0.02	0.06**	−0.00	0.07
	Gender		0.11**	0.07	0.12	−0.04
	Living location		−0.07***	−0.09**	0.02	−0.11**
	Respiratory conditions		−0.00	0.02	−0.00	0.02
Independent variables	Protection motivation	Well-being	0.11***	0.25***	0.01	0.25***
	Adoption intention		0.63***	0.55***	0.66***	−0.11
Control variables	Age		0.13***	0.19***	0.07	0.12*
	Number of children		−0.04	−0.04	0.00	−0.04
	Education		0.00	−0.05	0.03	−0.08
	Gender		−0.15***	−0.09	−0.22***	0.13
	Living location		0.04	−0.02	0.05	−0.06
	Respiratory conditions		0.11	−0.01	0.29***	−0.30**

Abbreviation: no = nonsignificant.
***p value < 0.01.
**p value < 0.05.
*p value < 0.10.

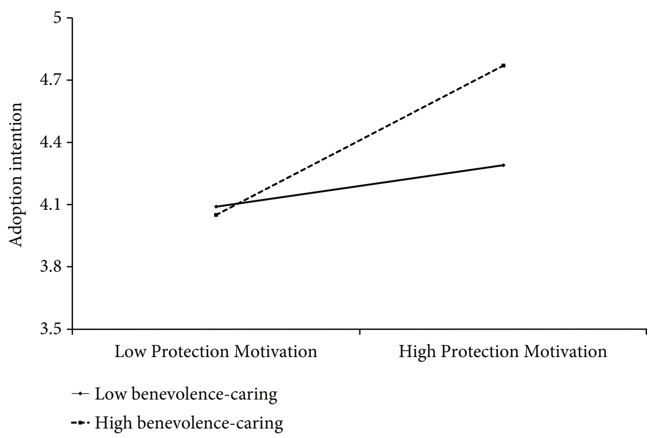

FIGURE 3: The moderating effect of benevolence–caring on the relationship between protection motivation and adoption intention for Germany.

aligns with prior studies on IAQ management technologies for asthma patients [14]. Also, in Portugal, women, when compared to men, place more value on having control over their health.

5.2. Practical Implications. Our study's findings suggest that public health campaigns and the advocacy of IAQ management technologies as a safeguard against poor IAQ should be tailored to address individual's feelings of worry and anxiety towards IAQ, emphasizing the efficacy of these technologies in mitigating poor IAQ, and improving health. This means that a focus on the severity of poor IAQ and response efficacy is more likely to yield substantial results than campaigns emphasizing vulnerability to the consequences of poor IAQ [65]. For example, campaigns could illustrate how IAQ management technologies, such as HEPA filters, are an effective response to wildland fires and pandemics, emphasizing their effectiveness in mitigating poor IAQ and protecting health [69, 70].

The noneffect of vulnerability also suggests that there should be sensitization campaigns regarding air pollutants' impact on people's health, as it has been linked to death and diseases [71, 72]. For example, educational initiatives could emphasize how even seemingly healthy individuals are at risk due to the cumulative effects of poor air quality over time, linking this to real-world examples to help shift public perception, making them more aware of the hidden dangers of air pollutants, thereby encouraging proactive adoption of IAQ management technologies.

The differences in how both countries access their coping strategies tell us that technology developers and marketeers should prioritize different aspects. In Germany, self-efficacy, response efficacy, and cost are determinants for technology adoption. Self-reliance and effectiveness are highly valued thus manufacturers could focus on developing products that are easy to install and operate independently. In the case of Germany, strategies should emphasize the idea that individuals can feel confident in navigating IAQ management technologies on their own and that there is reliable customer support and built-in help features. In Germany, they should also emphasize the contribution to the well-being of their close family and children and how they can benefit older individuals' health. For instance, campaigns could demonstrate how easy-to-use IAQ devices can empower users to take control of their health, and by extension, protect their loved ones. In contrast, in Portugal, where perceived effectiveness is significantly more important and the only determinant factor, promoting the effectiveness of these solutions is key to resonate with consumers.

Moreover, our study indicates that individuals from both countries already engaged in protective measures against poor IAQ are more inclined to adopt IAQ management technologies, with this transition being particularly smoother for younger generations [66]. Therefore, directing campaigns towards these demographics would likely be more effective. Given that younger individuals tend to be early adopters of technology, campaigns targeting this demographic could leverage digital platforms and social media to showcase the benefits of these technologies. For example, sharing testimonials and success stories of how young families have benefited from using air purifiers during recent fire seasons could reinforce the importance and effectiveness of these technologies.

For both countries, communication efforts should highlight how adopting these technologies leads to tangible health and well-being improvements [73], which has been a public concern since the beginning of the century regarding indoor environments [74]. In Portugal, a focus on how these technologies can help the health of individuals suffering from respiratory conditions should be effective. In Germany, this does not seem to be a determining factor, thus, we suggest sensitization campaigns, as it has been proved that long-term exposure to air pollutants increases the risk of asthmatic symptoms [75]. Health practitioners could be encouraged to recommend air purifiers and other IAQ technologies as part of their treatment plans, particularly for patients with asthma or allergies. Finally, particularly in Portugal, promotional strategies targeting women should focus on how these technological solutions can empower and bring positive outcomes to their health.

5.3. Limitations and Future Research. Several limitations have been identified that offer directions for future research. This study's first limitation is the adoption of a cross-sectional survey design, which challenges the ability to track trends, developments, or fluctuations in the variables under study. In future studies, it would be interesting to conduct a longitudinal investigation. The second limitation is regarding the utilization of IAQ management technologies as a broad concept incorporating several technologies, as there could be different results if we focus on only one. We suggest conducting an experimental investigation focusing on a specific IAQ management technology to determine if there are differences in the adoption of each technology.

Additionally, our study's generalizability is limited to the countries under examination. While this study focused on a comparative analysis between Germany and Portugal, we acknowledge that including more countries could provide a broader understanding of how cultural, economic, and social factors influence IAQ management. Relatedly, the model could directly integrate cultural variables within the quantitative analysis, which could facilitate cross-country comparisons. Furthermore, economic disparities, purchasing power differences, variations across subgroups within each country, and household family make-up were not considered as variables. However, future studies might incorporate socioeconomic indicators to better understand these dynamics.

Finally, it is worth noting that our study took a quantitative approach. In future investigations, it may be advantageous to use qualitative research techniques such as focus groups and expert and consumer interviews to enrich and validate our findings further.

6. Conclusion

This study explores the adoption of IAQ management technologies in Germany and Portugal, offering a cross-country perspective to better inform strategies for healthier indoor environments. Drawing on the PMT, our research uncovers distinct patterns in coping and threat appraisal regarding protection motivation and the adoption of IAQ management technologies. Our study suggests that effective campaigns should emphasize severity and response efficacy rather than vulnerability. We recommend targeting individuals already practicing protective behaviors, especially younger generations, as they are more likely to adopt IAQ management technologies. Additionally, promoting these technologies should highlight positive health outcomes and health empowerment.

The observed variations in the model's performance between Germany and Portugal emphasize the importance of tailoring communication in public health campaigns to specific cultural contexts. For instance, only in Germany, self-efficacy and contributing to the well-being of family and friends are emphasized. We also propose sensitization campaigns to educate individuals in both countries on the health consequences of poor IAQ, leveraging the public's growing familiarity with protective technologies and the evolving public awareness, influenced by events such as the COVID-19 pandemic and increased occurrences of wildland fires.

Data Availability Statement

Data is available upon request.

Ethics Statement

The electronic questionnaire was approved by the NOVA IMS Ethics Committee with the ethical approval reference number INFSYS2024-5-62451. All participants gave us their informed consent to participate in the study.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)* The supporting information includes four tables: Table S1. Questionnaire items for measuring each construct. Table S2. Sample characteristics. Table S3. Loadings and cross-loadings. Table 4. Heterotrait–monotrait (HTMT) ratio.

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