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Indoor air quality perception: Enablers and inhibitors of perceived occupant comfort

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ABSTRACT

Growing environmental and public health concerns have increased the need for healthy buildings, with indoor air quality (IAQ) emerging as a priority. While technological advancements in IAQ management have progressed, research often overlooks individual comfort perception and behavioral factors influencing it and disconnects IAQ improvements from behavioral insights. This study explores how personal characteristics, perceived inhibitors, and enablers shape comfort perception in indoor environments managed by Internet of Things-based IAQ management technologies (IAQMTs). Given the EU's growing emphasis on smart, energy-efficient, and occupant-centered buildings, we examine comfort perceptions across seven European countries to inform user-centered IAQ strategies aligned with policy goals. Grounded in the dual-factor theory, we employed a survey-based approach in the European context and analyzed responses from 2800 individuals using partial least squares structural equation modeling (PLS-SEM). Our model demonstrated strong explanatory power, accounting for over 65 % of the variance in perceived IAQ and comfort in public environments. Key enablers are intuitiveness, response efficacy, and hedonic motivation, while convenience is not. Information and privacy concerns are not inhibitors. Health consciousness and environmental consciousness are important individual characteristics when it comes to perception. Perceived good IAQ was the strongest predictor of comfort in public spaces. The findings emphasize the importance of intuitive, transparent, and engaging IAQMTs that visibly demonstrate pollutant reduction and comfort enhancement. We recommend that building managers and technology developers incorporate user-centered features, such as clear interfaces, gamification elements, personalized controls, and communication strategies highlighting health and environmental benefits, to foster adoption and improve occupant comfort. Our findings support a human-centered approach, integrating behavioral insights into environmental health science, focusing beyond technical metrics and more on occupant beliefs and perceptions, supporting strategies that align with user needs and EU goals.

1. Introduction

The growing awareness of environmental concerns such as climate change, pollution, decreased urban livability, an aging population, heightened stress levels, longer working hours, and the enduring impacts of the COVID-19 pandemic has escalated the urgency to prioritize healthy buildings (Awada et al., 2021). In this study, we are focusing on a fundamental part of this equation: indoor air quality (IAQ) perception and comfort in public indoor environments. IAQ remains a critical issue due to the elevated presence of contaminants, such as fine particulate matter (PM2.5) and carbon dioxide (CO2), which often exceed established building guidelines (Baloch et al., 2020; Kumar et al., 2023). Prolonged exposure to these pollutants contributes to a reduction in quality-adjusted life years and increases the likelihood of premature mortality (Bui et al., 2023; Hall et al., 2024). Beyond mortality risks, inadequate IAQ is associated with adverse effects such as respiratory problems, allergic reactions, decreased cognitive and physical performance, poor sleep, and reduced comfort (Deng et al., 2024; Felgueiras et al., 2023).

In response to these challenges, technology has shown strong

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potential in improving and managing indoor air quality (IAQ) by detecting, monitoring, and reducing pollutant levels through various IAQ management solutions, including sensors, wearables, and portable devices (Čulić et al., 2022; Kaginalkar et al., 2021). For instance, air purifiers across various settings, such as schools, workplaces, and homes, have shown the positive impact they have on IAQ and occupant comfort (Cheek et al., 2021; Cooper et al., 2021). Current studies further emphasize the value of integrated technologies for high-performance buildings, showing that smart IAQ solutions, such as internet of things (IoT) enabled heating, ventilation, and air conditioning systems with filtration units, can improve occupant comfort by monitoring environmental conditions and adjusting IAQ dynamically (Banerjee et al., 2021; Hadj Sassi and Chaari Fourati, 2022). The deployment of these technologies not only enhances thermal comfort and IAQ but also adds economic value to buildings, making them more desirable than facilities with basic amenities (Berto et al., 2023; Cooper et al., 2021). While these systems offer tangible benefits, their success also depends on how individuals perceive and interact with them.

IAQ management research often emphasizes direct intervention testing, focusing on technical performance, pollutant reduction, and health outcomes (Deng et al., 2024; Fan et al., 2024). Some recent studies on technology for IAQ management have taken a behavioral approach, but the approach is still narrow, as the focus tends to be on technology adoption and mitigation behaviors (Chen and Liu, 2023; Shahbaz et al., 2021), largely overlooking the influence of individual characteristics and enablers or barriers that shape individual comfort perceptions. Previous research assessing perceived air quality in indoor environments has taken a survey approach and focused on factors such as air acceptability, odor intensity, and satisfaction (Torriani et al., 2024). Research that captures how individuals perceive IAQ, beyond whether it meets certain thresholds, is essential for designing and managing occupant-centered environmental solutions, as it treats building occupants as active agents rather than passive recipients of air conditions.

To address this gap, this study adopts a behavioral approach, as we investigate the factors impacting individuals' comfort perceptions and beliefs in indoor environments managed by IoT-based indoor air quality management technologies (IAQMTs). Individual perception is vital because it captures how people experience and evaluate indoor air conditions. Specifically, our exploratory research, which builds on the dual-factor theory (DFT), investigates how individuals' perceptions of inhibitors, such as privacy and information concerns, and enablers, such as hedonic motivation, intuitiveness, convenience, and response efficacy, can impact comfort perception. We also explore how individual characteristics, such as health and environmental consciousness, can shape comfort perception. Comfort perception is addressed using two dimensions: comfort provided by perceived improved IAQ and perceived comfort in public environments. To do this, we conducted a large-scale survey across seven European countries and analyzed the data using partial least squares structural equation modeling (PLS-SEM). By investigating these behavioral dimensions across multiple European countries, this study seeks to bridge the gap in IAQ management research by incorporating a behavioral perspective that emphasizes the role of individual perceptions regarding IAQ and management technologies.

This research makes several contributions to the literature and practice of environmental management. First, it adapts the DFT to a novel context and extends it by incorporating individual-level characteristics, thus offering a more comprehensive lens on how personal and environmental factors interact. Second, it introduces and validates new scales designed to subjectively capture IAQ and comfort, providing future researchers with reliable measurement tools for further investigation, addressing a need for occupant-centered research instruments. Third, this research is a step in understanding how specific factors drive comfort through IAQ management, offering insights on human interaction with the indoor built environment to generate positive occupant perceptions. Understanding these factors advances the intersection of environmental management and behavioral research, demonstrating that comfort is driven not only by IAQ metrics but also by user experience, which can encourage a more holistic approach to environmental management that balances measurable IAQ improvements with human perception.

2. Literature review and research framework

2.1. Technological approach to IAQ management

Managing indoor air quality (IAQ) has become a prominent global concern as governments recognize its crucial role in public health, particularly within urban environments where rapid urbanization and economic expansion contribute significantly to indoor pollution levels (Coggins et al., 2022; Singh et al., 2021). Public buildings, such as schools, hospitals, and workplaces, increasingly face challenges in maintaining healthy indoor air conditions due to the compounded effects of outdoor pollution, human activities, and building design (Pulimeno et al., 2020; Siddique et al., 2023). Specifically in Europe, the topic of IAQ has been central for the European Commission, which has been financing research projects, implementing new directives, and having multiple organs responsible for addressing and exploring issues related to IAQ. These efforts reflect a growing recognition that safeguarding IAQ is a public policy priority with direct implications for health, comfort, and environmental sustainability. Given the significant effects of IAQ on occupant health and comfort, it is essential to implement effective strategies to monitor and improve air quality in indoor spaces.

Numerous strategies have been proposed to address these challenges, with particular emphasis on integrating smart and Internet of Things (IoT) technologies (Burroughs and Hansen, 2023; Dai et al., 2023). These IoT-based IAQ management technologies enable real-time monitoring and control of pollutants, including volatile organic compounds (VOCs), carbon dioxide (CO_2), and small particulate matter (PM2.5), allowing for prompt adjustments to air quality management systems and improving overall air quality (Son et al., 2023). They provide a data-driven approach that continuously adjusts air quality parameters to meet recommended standards for indoor environments. Recognizing the value of such technologies, the recently updated European Union's (EU) Energy Performance of Buildings Directive explores how energy-efficient designs and smart building technologies can optimize indoor environmental quality (IEQ), achieving health and comfort while ensuring sustainability (European Commission, 2025). This direction is also reflected in the EU's Smart Readiness Indicator (SRI), which aims to promote smart buildings to enhance occupant comfort, energy efficiency, and achieve environmental goals (Verbeke et al., 2020).

2.2. The role of perception in IAQ management

Most studies on IAQMTs emphasize the direct testing of interventions for predicting pollutant levels (Borah et al., 2024; Patra et al., 2016), monitoring pollutants (Becerra et al., 2020; Mohd Nadzir et al., 2021), and examining their impacts on health and environmental outcomes (Cheek et al., 2021; Fong et al., 2021). While such technical evaluations are essential, they tend to overlook the human dimension of IAQ, namely, how people perceive, evaluate, and respond to IAQMTs. The success of these technologies ultimately depends heavily on how individuals perceive and interact with them. Individuals' understanding and perception of IAQ influences both compliance with guidelines and the adoption of new technologies (Sun et al., 2024; Veiga et al., 2024). This underscores the importance of integrating perceptual and behavioral factors into IAQ management. One key concept in this regard is comfort perception, a subjective but central experience that reflects how occupants interpret environmental conditions in indoor spaces. Comfort has become an increasingly important concern in IAQ discussions, not only for its link to health and well-being but also because of its growing economic relevance in commercial and residential buildings (Andargie et al., 2019; Awada et al., 2022).

Comfort is a subjective experience arising from the interpretation of environmental factors interacting with us physically, physiologically, and individually, and represents a fundamental human need closely tied to health, satisfaction, and well-being (Altomonte et al., 2024; Cicerali et al., 2017). Occupants' perceptions, such as a feeling of freshness or cleanliness, can be more telling of comfort and satisfaction than objective IAQ measures alone (Torriani et al., 2024). As such, evaluating IAQ interventions solely through objective indicators may miss critical aspects of user experience. People's perception of air pollution often doesn't align with their objectively measured exposure, as they may underestimate or overestimate pollution levels, depending on the specific context, such as using public transportation, where individuals tend to perceive lower levels of IAQ (Song and Kwan, 2023). This perception bias implies that occupants' sense of comfort or safety can rely more on situational cues, like odor or visible haze, than on actual pollutant levels, highlighting the importance of factoring in both objective measurements and subjective experiences when designing or implementing IAQ interventions.

2.3. Enablers and inhibitors of IAQ and comfort perception: The dual-factor theory

Cenfetelli (2004) proposed a technology adoption model that introduced the idea of dual-factor concepts. The theory distinguishes between two separate categories of variables, those being enablers and inhibitors, that influence an individual's decision to use or reject a system or technology (Cenfetelli, 2004). This approach fills the gap left by other technology adoption models, which only focus on the positive beliefs regarding the technology and ignore the aspects that might discourage its use (Cenfetelli and Schwarz, 2011). Enablers are the individual's beliefs regarding a system's attributes that can positively influence or motivate individuals to adopt technology. They are related to the design, functionalities, and quality of a system, including factors such as reliability and responsiveness (Cenfetelli, 2004). In contrast, inhibitors are perceived factors that act solely as barriers and can prevent an individual from adopting a system. Examples of a system's negative attributes are the perceived risks and intrusiveness (Cenfetelli and Schwarz, 2011). Furthermore, the author recognized that individual and environmental factors can play a role in this dynamic.

DFT has proven instrumental in exploring the enablers and inhibitors in a varying number of contexts and explaining a diverse set of target variables in studies from leading journals, highlighting its applicability across diverse domains. For instance, it has been used to understand consumers' organic food purchase behavior (Tandon et al., 2021), households' waste separation intention (Kushwah et al., 2023), archeological tourism (Rodríguez and Pérez, 2022) digital hoarding behavior (Vinoi et al., 2024a, Vinoi et al., 2024b), positive and negative word of mouth (Das and Ramalingam, 2023; Talwar et al., 2021), smartphone loyalty (Lin et al., 2015), intention to use ophthalmic AI devices (Ye et al., 2019), attitude toward telehealth (Tsai et al., 2019), and satisfaction with mobile payments (Sharma and Mishra, 2023). Therefore, DFT offers a robust framework for understanding the enablers and inhibitors associated with IAQ management technologies to create comfortable environments and allows us to incorporate individual factors to study this phenomenon.

2.3.1. Enablers

Hedonic motivation has been extensively studied in the context of technology adoption (Venkatesh et al., 2012). However, to our knowledge, no studies have approached its direct impact on comfort. Nevertheless, the impact of comfort on hedonic motivation has shown a significant impact (Ainsworth and Foster, 2017). Furthermore, there have been promising results in similar studies where well-being is studied as an outcome. Hedonic motivation has shown a direct impact on well-being in the context of IoT smart homes (Sequeiros et al., 2022) and has been proven to be a moderator for well-being, in the context of sustainable technologies (Mateus et al., 2023). Therefore, we hypothesize that individuals who perceive more enjoyment from using IAQ management technologies have a more positive perception of IAQ and comfort through IAQ solutions.

H1a: Hedonic motivation enables indoor air quality perception.

H1b: Hedonic motivation enables comfort in public environments.

Convenience refers to the idea of technology giving individuals a set of convenient features to achieve greater IAQ control (Baudier et al., 2020). The European Union describes convenience as a key impact criterion of smart readiness in buildings, defined by the extent to which smart technologies can simplify life for occupants, such as through fewer required manual interactions and more automation (Verbeke et al., 2020). IoT supports occupant comfort but also optimizes energy use based on real-time data, demonstrating IoT's dual benefits of improving user convenience and enhancing energy efficiency within smart buildings (Parkinson et al., 2019). Thus, we hypothesize that individuals are more likely to perceive that using IAQ management technologies can improve IAQ and comfort in public environments if they perceive the technology has features to make managing IAQ more convenient:

H2a: Convenience enables indoor air quality perception.

H2b: Convenience enables comfort in public environments.

Intuitiveness conveys the idea of intuitiveness when setting up and interacting with IAQ solutions. That is, technology should be intuitive to use. The concept of intuitiveness has become very relevant in the context of IoT and smart technologies, as it plays a crucial role in shaping user experiences and facilitating seamless interactions with connected devices and systems (Curry et al., 2020; Shin, 2017). Research on smart homes emphasizes user-centric designs with seamless integration, easy and intuitive use, and straightforward interfaces to enhance user satisfaction and make these technologies a natural part of daily life (Cui et al., 2024). Therefore, we hypothesize that individuals who expect IAQ solutions to be intuitive to connect, set up, and interact with will have a more pleasant user experience and thus, feel greater control over their comfort level.

H3a: Intuitiveness enables indoor air quality perception.

H3b: Intuitiveness enables comfort in public environments.

Response efficacy has been extensively studied in the context of health informatics and has proved to be relevant in predicting the adoption of protective behaviors (Laugesen and Hassanein, 2017; Veiga et al., 2024). The concept conveys the idea of technology being an effective response or mechanism to safeguard individuals from the negative consequences of poor IAQ. IAQ management technologies have proved to be effective in diverse environments like vehicles, homes, and classrooms, where they significantly reduce particulate matter (PM) and other pollutants (Fong et al., 2021; Woo et al., 2023) and protect against viruses and bacteria (Elsaid and Ahmed, 2021; Pirouz et al., 2021). Thus, we hypothesize that using IAQ solutions that are perceived to be effective in protecting oneself and in improving the IAQ will impact the perception of IAQ and comfort in public environments.

H4a: Response efficacy enables indoor air quality perception.

H4b: Response efficacy enables comfort in public environments.

2.3.2. Inhibitors

Privacy concern is the level of concern or stress a user experiences, regarding the opportunistic behavior of IAQ solutions vendors concerning their private information. In the European Union, users' privacy is an important matter regulated by the General Data Protection Regulation (GDPR) and it has been proven to be an inhibitor of health-related technology adoption (Li et al., 2016; Li et al., 2019; Tran and Nguyen, 2021). Previous research underscores the importance of safety and privacy considerations, which can pose challenges to improving IAQ, even with more traditional methods such as opening windows (Dimitroulopoulou et al., 2023; Tsoulou et al., 2021). When it comes to smart and IoT technology cybersecurity is always a central matter as it can deter adoption and cause harm to its users (Mocrii et al., 2018; Verbeke et al., 2020). This notion could be applied to this context, as users might struggle to feel comfortable indoors or their perception might be influenced negatively if they dońt feel their privacy requirements are being met.

H5a: Privacy concerns inhibit indoor air quality perception.

H5b: Privacy concerns inhibit comfort in public environments.

Information concern can be defined as the extent to which a user expresses concern or experiences stress regarding the accuracy and reliability of IAQ data acquired through IAQ solutions (Marakhimov and Joo, 2017). IoT-based IAQ systems can provide reliable data; however, users might feel the data the sensors gather is not reliable due to concerns about sensor calibration, environmental variability affecting sensor performance, and the lack of transparency in data processing methods (Dai et al., 2023). Therefore, we hypothesize that individuals worried about data accuracy will be less confident in the ability of the technology to improve indoor air quality and comfort and thus their perception will be impacted negatively:

H6a: Information concern inhibits indoor air quality perception.

H6b: Information concern inhibits comfort in public environments.

2.3.3. Individual characteristics

Health consciousness refers to individuals who prioritize their health and embrace behaviors focused on wellness and thus are inclined to engage in preventive health practices, such as being interested in information about their health and being concerned with what they eat (Chang et al., 2022; Jayanti and Burns, 1998). In the context of our study, we expect individuals who are more conscious of their health will be able to better understand how these technologies can contribute to their comfort. Therefore, we hypothesize that:

H7a: Health consciousness positively influences indoor air quality perception.

H7b: Health consciousness positively influences comfort in public environments.

Environmental consciousness can be defined as an individual's orientation toward protecting the environment (Shi et al., 2017). Growing awareness of environmental issues such as climate change and pollution has brought to attention the significant threat they pose to human health, impacting both outdoor and even more indoor environments, thereby requiring enhanced health considerations in buildings (Awada et al., 2021). Environmental consciousness involves acknowledging environmental issues but also supporting efforts and taking personal action to solve those issues (Lin and Chang, 2012; Paul et al., 2016). Therefore, we hypothesize that individuals who are more aware of environmental issues can better perceive how IAQ solutions can impact their comfort.

H8a: Environmental consciousness positively influences indoor air quality perception.

H8b: Environmental consciousness positively influences comfort in public environments.

The COVID-19 pandemic made us rethink building design and safety features, especially in crowded environments, which further pose health risks (Park et al., 2022). Improving indoor air quality through innovative, safe, and efficient ventilation solutions is essential for protecting occupants, particularly in high-occupancy buildings (M. Fan et al., 2022; Lipinski et al., 2020). For instance, IoT sensors can monitor environmental quality and detect hazardous substances, contributing to a safer school environment (Kitkowska et al., 2024). Therefore, we hypothesize that if individuals perceive good IAQ levels they will feel more comfortable in public indoor environments, such as public transportation and waiting areas.

H9: Indoor air quality perception positively influences comfort in public environments.

3. Research methods

3.1. Research framework

This study builds on the DFT as the theoretical foundation to develop a model explaining the factors that influence individuals' perception of IAQ and comfort in public environments managed by IAQMTs. The research model, presented in Fig. 1, distinguishes between enablers, which are positive drivers of user perception, and inhibitors, which are factors that may hinder the perception of comfort. Enablers, including hedonic motivation, convenience, intuitiveness, and response efficacy, are hypothesized to positively impact comfort in terms of IAQ perception, as reflected by hypotheses H1a to H4a, and comfort in public environments, as reflected by hypotheses H1b to H4b. Inhibitors, such as privacy and information concerns, are expected to negatively affect comfort in terms of IAQ perceptions, as shown in hypotheses H5a and H6a, and comfort in public environments, as shown in hypotheses H5b and H6b. The model also incorporates the role of the individual factors, health consciousness, hypothesized under H7a and b, and environmental consciousness, hypothesized under H8a and b, in shaping comfort perceptions. Finally, age, education, number of children, gender, location, and respiratory conditions are introduced as control variables.

3.2. Questionnaire design

The variables in our model were measured using items derived from both existing literature and a qualitative investigation consisting of 21 in-depth interviews, to help identify and customize factors to suit the specific context of our study. Wherever possible, we relied on existing, validated scales to design our survey tool. However, variables like intuitiveness and comfort in public environments, highlighted by our interviewees, required us to develop new items using a reflective measurement approach. These self-developed items were crafted by synthesizing statements from the interviewees to ensure a comprehensive and contextually relevant set of items for each construct. An expert panel, including faculty members with survey design expertise and IAQ specialists, reviewed the items to evaluate clarity and the necessary wording adjustments. We implemented minor refinements based on the panel's feedback to improve item clarity.

The full questionnaire, crafted in English, was carefully reviewed by academic researchers and then translated by native speakers into each language required for the countries where it was administered. These translations were rigorously reviewed by native speakers of each language and subsequently back-translated to ensure accuracy. The items in the questionnaire were assessed using a 7-point range scale, ranging from "strongly disagree" (1) to "strongly agree" (7). Additionally, our questionnaire included sociodemographic questions, such as age, gender, and education level, to characterize the sample better. Before deployment, the final questionnaire was tested in a pilot study with 213 individuals, and the measurement model was evaluated, confirming its consistency, validity, and reliability. For the detailed items, please refer to Table A1 in Appendix A.

3.3. Data collection

The questionnaire received approval from the university's ethics committee, and informed consent was obtained from all participants before their involvement in the study. To collect quantitative data, we used a survey approach (Kushwah et al., 2023; Wang et al., 2024) targeting individuals from seven European countries: Germany, Greece, Ireland, Spain, Sweden, the UK, and Portugal. Given that participants could be unfamiliar with the topic of IAQ and technologies to manage it, an introductory video was played, and definitions were presented before each questionnaire session to ensure respondents' comprehension of the concepts. The data collection for the quantitative phase took place in the last half of July 2023, and the participants were randomly recruited

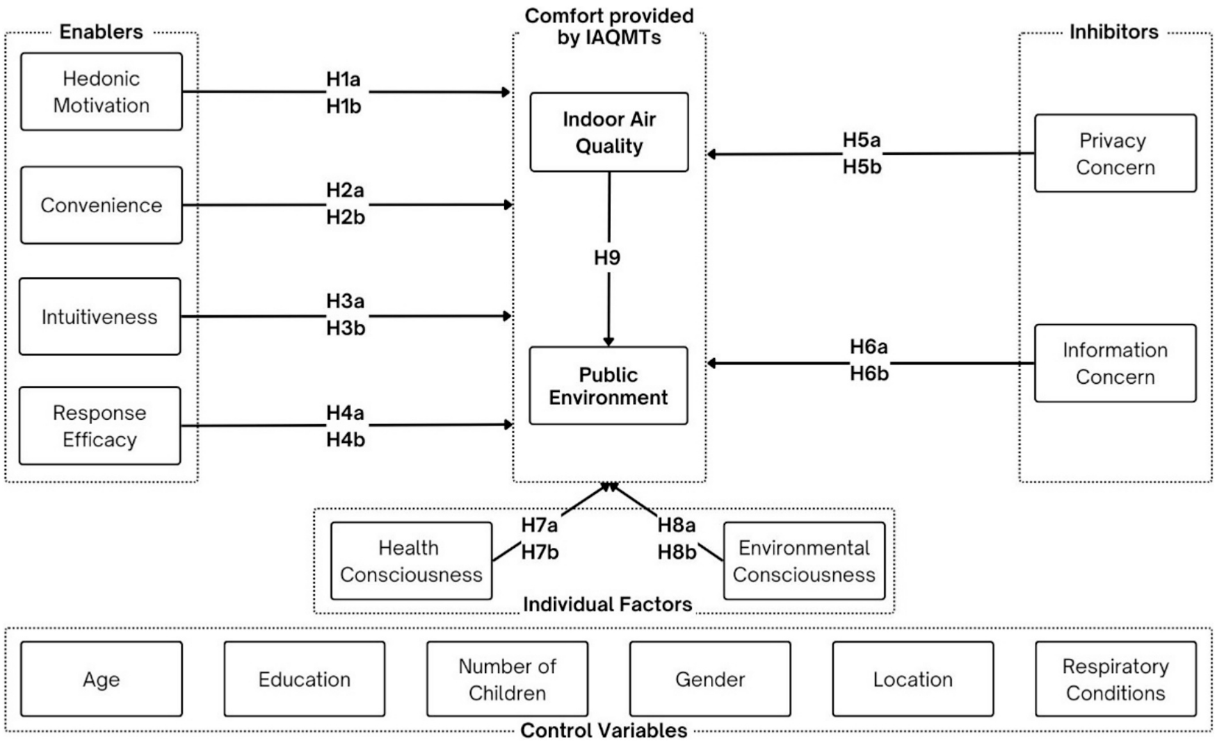

Fig. 1. Research model.

Table 1
Quantitative study sample characteristics with percentages.

Sample Characteristics		Overall (N = 2800)	Germany (n = 400)	Greece (n = 400)	Ireland (n = 400)	Portugal (n = 400)	Spain (n = 400)	Sweden (n = 400)	UK (n = 400)
Gender	Male	1375 (49 %)	196 (49 %)	199 (50 %)	200 (50 %)	188 (47 %)	196 (49 %)	200 (50 %)	196 (49 %)
	Female	1425 (51 %)	204 (51 %)	201 (50 %)	200 (50 %)	212 (53 %)	204 (51 %)	200 (50 %)	204 (51 %)
Age	<35	1186 (42 %)	146 (37 %)	156 (39 %)	199 (50 %)	147 (37 %)	157 (39 %)	193 (48 %)	188 (47 %)
	36–49	495 (18 %)	65 (16 %)	73 (18 %)	78(19 %)	81 (20 %)	79 (20 %)	55 (14 %)	64 (16 %)
	>50	1119 (40 %)	189 (47 %)	171 (43 %)	123 (31 %)	172 (43 %)	164 (41 %)	152 (38 %)	148 (37 %)
Living area	City center	1240 (44 %)	199 (50 %)	230 (57 %)	111 (28 %)	189 (47 %)	232 (58 %)	141 (35 %)	138 (34 %)
	City outskirts	606 (22 %)	72 (18 %)	82 (20 %)	79 (20 %)	113 (28 %)	72 (18 %)	108 (27 %)	80 (20 %)
	Suburban area	546 (20 %)	50 (12 %)	61 (15 %)	118 (30 %)	39 (10 %)	64 (16 %)	75 (19 %)	139 (35 %)
	Countryside	408 (15 %)	79 (20 %)	27 (7 %)	92 (23 %)	59 (15 %)	32 (8 %)	76 (19 %)	43 (11 %)
Education	No qualifications	9 (0 %)	2 (0 %)	0 (0 %)	3 (1 %)	0 (0 %)	0 (0 %)	0 (0 %)	4 (1 %)
	Primary school	46 (2 %)	4 (1 %)	1 (0 %)	5 (1 %)	2 (0 %)	4 (1 %)	28 (7 %)	2 (0 %)
	High school	868 (31 %)	33 (8 %)	118 (30 %)	127 (32 %)	134 (34 %)	95 (24 %)	206 (52 %)	155 (39 %)
	Apprenticeship	417 (15 %)	169 (42 %)	20 (5 %)	33 (8 %)	42 (10 %)	106 (26 %)	18 (4 %)	29 (7 %)
	Bachelor's degree	1013 (36 %)	117 (29 %)	197 (49 %)	146 (36 %)	150 (38 %)	148 (37 %)	112 (28 %)	143 (36 %)
	Master's degree	357 (13 %)	62 (16 %)	52 (13 %)	61 (15 %)	60 (15 %)	37 (9 %)	31 (8 %)	54 (14 %)
	Doctoral degree	90 (3 %)	13 (3 %)	12 (3 %)	25 (6 %)	12 (3 %)	10 (2 %)	5 (1 %)	13 (3 %)
Number of children	0	1244 (44 %)	140 (35 %)	198 (50 %)	192 (48 %)	165 (41 %)	166 (42 %)	210 (52 %)	173 (43 %)
	1	645 (23 %)	122 (30 %)	79 (20 %)	72 (18 %)	99 (25 %)	96 (24 %)	64 (16 %)	113 (28 %)
	2	684 (24 %)	116 (29 %)	94 (24 %)	90 (22 %)	116 (29 %)	112 (28 %)	83 (21 %)	73 (18 %)
	3	163 (6 %)	17 (4 %)	21 (5 %)	32 (8 %)	15 (4 %)	18 (4 %)	32 (8 %)	28 (7 %)
	≥4	64 (2 %)	5 (1 %)	8 (2 %)	14 (4 %)	5 (1 %)	8 (2 %)	11 (3 %)	13 (3 %)
Respiratory conditions	Yes	446 (16 %)	82 (20 %)	58 (14 %)	74 (18 %)	61 (15 %)	60 (15 %)	63 (16 %)	48 (12 %)
	No	2354 (84 %)	318 (80 %)	342 (86 %)	326 (82 %)	339 (85 %)	340 (85 %)	337 (84 %)	352 (88 %)

online.

To determine an appropriate sample size, we applied the infinite population size model (Bihu, 2021) while adopting a pessimistic assumption ($p = 0.50$), using a 95 % confidence level, and a 5 % margin of error. A pessimistic assumption is a conservative choice that ensures we collect enough responses to handle the most uncertain scenario. By applying Eq. (1), where n is the required sample size, Za/2 is the z-score associated with the confidence level for a two-tailed test, p is the assumed proportion in the population, and E is the desired margin of error, we obtained a minimum required sample size of 385. Consequently, our final dataset of 2800 complete survey responses comfortably exceeds this threshold, ensuring robust statistical power and precision for hypothesis testing.

$$n = \frac{z^2_{\alpha \div 2} \times p(1-p)}{E^2} \quad (1)$$

Eq. (1). Standard formula for estimating a proportion in an infinite population.

To ensure representativeness, quotas for age and gender were applied during data collection. The proportion test confirmed no statistically significant discrepancies between the population and our sample distributions across these demographics, confirming that the sample is representative of the general population in terms of age and gender. Although variables such as education and number of children are reported and included in the model, they were used primarily as control variables to account for heterogeneity, rather than for independent subgroup analysis. Therefore, no separate sample size calculations were conducted for these subgroups. Table 1 details the sample distribution by characteristics. A large portion of the sample lives in urban areas, particularly in the city center, does not have children, and has a high school diploma or a bachelor's degree.

After data collection, to address common method bias, two approaches were employed. First, we validated the variance inflation factors (VIF) values in the inner model, which were all below the threshold of 3.3, indicating no significant bias (Kock and Lynn, 2012; Pontes et al., 2024). Additionally, we conducted Harman's single-factor test, which revealed that no single factor accounted for more than 50 % of the variance, further supporting the absence of common method bias (Podsakoff et al., 2003).

3.4. Data analysis method

We evaluated the research model using the partial least squares structural equation modeling (PLS-SEM) method, which has been previously used in the context of environmental management (W. Wang et al., 2023). This was driven by the complexity of our model, which comprises multiple constructs and indicators, and the exploratory nature of our research (Hair et al., 2019). We used the software SmartPLS 4 to assess the measurement model to evaluate construct reliability, indicator reliability, convergent validity, and discriminant validity (Ringle et al., 2023). To interpret the structural model and analyze the significance of the path coefficients, we employed PLS-SEM bootstrapping, which involves iteratively resampling the dataset. To ensure consistent results, we utilized 10,000 iterations (Hair et al., 2021).

4. Results

4.1. Measurement model

Internal consistency was appraised through composite reliability (CR), which determines the reliability of our constructs (Hair et al., 2021). Additionally, convergent validity was established by examining the indicators' outer loadings and the average variance extracted (AVE). In Table 2, each construct demonstrates a CR exceeding the threshold of 0.7, while the diagonal elements, representing the square root of AVE, exceed the correlations between constructs (Hair et al., 2021). This indicates the indicators measuring each construct are reliable and share variance. Discriminant validity was also evaluated, focusing on the cross-loadings (Table A2 in Appendix A) and the Heterotrait-Monotrait (HTMT) ratio of correlations (Table A3 in Appendix A). Notably, all loadings surpass 0.60, a recommended threshold for exploratory research, and exceed the cross-loading values (Hair et al., 2019). Furthermore, all HTMT diagonal values fall below the 0.90 threshold (Hair et al., 2019), confirming that our constructs are distinct from each other and are measuring unique underlying concepts (Hair et al., 2021).

4.2. Structural model

Our results reveal a robust overall model, with high explanatory power across the target variables, as evidenced by the R-squared (R^2) values above 65 %, which measure how much of the variation in a target variable is explained by the model. As shown in Fig. 2, we find that the perceived IAQ provided by IAQMTs is explained by our model at 66.3 %, and the perceived comfort provided by IAQMTs in a public environment is explained at 65.6 %. Privacy and information concerns, which we identified as inhibitors, showed no impact on our target variables, leading us to reject hypotheses 5 and 6. Among the enablers, hedonic motivation, intuitiveness, and response efficacy had a statistically significant impact, whereas convenience did not. Consequently, we confirmed hypotheses 1, 3, and 4, and rejected Hypothesis 2. Among individual factors, health consciousness has a statistically significant impact on both our target variables, confirming hypothesis 7. In contrast, environmental consciousness is only statistically significant in explaining perceived indoor air quality, confirming hypothesis 8a and leading to the rejection of hypothesis 8b. Therefore, 10 out of our 17 hypotheses were confirmed. When it comes to perceived IAQ, intuitiveness proved to be the strongest enabler, followed by response efficacy. Regarding public environments, the most important predictor is

Table 2
Total sample descriptive statistics: mean, standard deviation (SD), Cronbach alpha (CA), composite reliability (CR), correlations, and the square root of average variance extracted (AVE) (in italics).

	Mean	SD	Cα	CR	HM	Cnv	Int	RE	PC	IC	HC	EnC	IAQ	PEC
HM	4.672	1.610	0.919	0.933	*0.928*									
Cnv	5.136	1.461	0.948	0.948	0.655	*0.891*								
Int	5.810	1.210	0.956	0.956	0.394	0.555	*0.889*							
RE	5.370	1.387	0.923	0.925	0.631	0.758	0.625	*0.902*						
PC	4.572	1.752	0.964	0.978	0.085	0.087	0.077	0.034	*0.949*					
IC	4.287	1.685	0.946	1.162	0.139	0.148	0.075	0.064	0.648	*0.922*				
HC	5.098	1.684	0.868	0.874	0.569	0.619	0.426	0.574	0.225	0.288	*0.846*			
EnC	5.529	1.413	0.854	0.857	0.445	0.567	0.563	0.593	0.127	0.116	0.653	*0.835*		
IAQ	5.836	1.267	0.918	0.918	0.518	0.612	0.713	0.729	0.025	0.040	0.507	0.588	*0.927*	
PEC	5.621	1.396	0.928	0.929	0.521	0.599	0.650	0.684	0.053	0.071	0.514	0.558	0.773	*0.907*

HM: Hedonic motivation; Cnv: Convenience; Int: Intuitiveness; RE: Response efficacy; PC: privacy concern; IC: Information concern; HC: Health consciousness; EnC: Environmental consciousness; IAQ: Indoor air quality; PEC: public environment comfort.

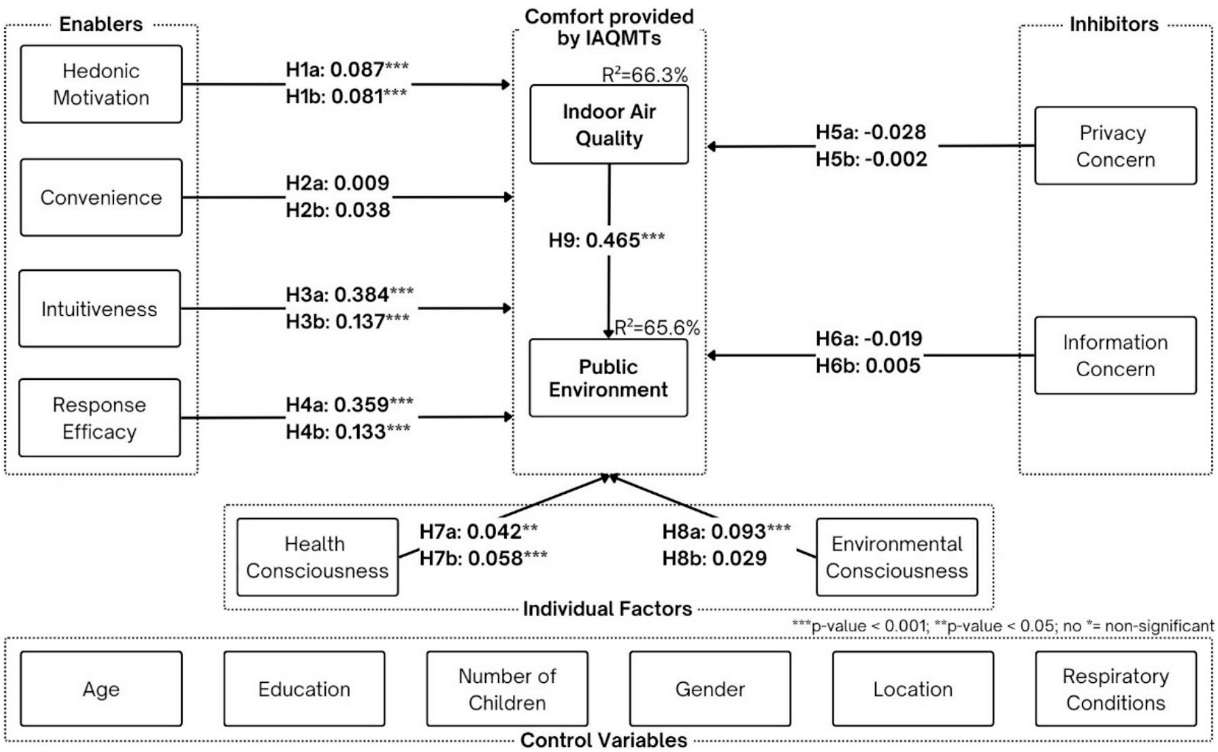

Fig. 2. Structural model results.

perceived good IAQ, followed by intuitiveness and response efficacy. The results of the control variables are available in Appendix B, Table B1.

4.3. Key enablers and inhibitors across countries

Our results show that intuitiveness and response efficacy are the most consistent and influential enablers of IAQ perception across all countries. These variables were significant in every national sample, with intuitiveness ranging from $\beta = 0.261$*** in Germany to $\beta = 0.492$*** in Sweden, and response efficacy ranging from $\beta = 0.247$*** in Ireland to $\beta = 0.424$*** in Portugal. Thus, IAQMTs must be perceived as both usable and effective to positively shape users' experience, as when individuals find the technology intuitive and believe it leads to real improvements in air quality, they are more likely to report positive perceptions of IAQ. IAQ perception itself is the strongest predictor of public environmental comfort in all countries, ranging from $\beta = 0.232$*** in Germany to $\beta = 0.566$*** in Portugal. This confirms that improving IAQ perception enhances how comfortable and safe individuals feel in public indoor settings.

In contrast, inhibitors such as privacy and information concerns were largely non-significant. One possible explanation for the general lack of significance is the widespread implementation of data protection frameworks like the GDPR, which may reduce privacy-related apprehension and allow users to focus more on perceived benefits. The exception was information concern in Greece, which negatively influenced IAQ perception ($\beta = -0.122$***), which means individuals are more likely to question the validity or utility of IAQ data, showing that in settings where trust is weaker, users may scrutinize data more critically or disengage when clarity is lacking. Other variables, while important in specific contexts, show more variability. For instance, environmental consciousness is a significant enabler in Greece, Ireland, Portugal, Spain, and the UK, but not in Germany or Sweden, possibly reflecting different individual priorities tied to culture. Hedonic motivation contributes to IAQ perception and public comfort in Germany, Spain, Sweden, and the UK, but is not significant in Greece, Ireland, or Portugal, suggesting a cultural link to enjoyment and engagement with technology. Convenience is generally not significant, and even negatively associated with IAQ perception in the UK ($\beta = -0.165$***), possibly reflecting preferences for control over automation.

While enablers, such as intuitiveness and response efficacy, are universal, others vary across national contexts, highlighting the need for a dual approach that maintains core usability principles while adapting communication and design strategies to local expectations and values. IAQMTs should prioritize intuitiveness and clear communication of effectiveness, as these features are fundamental to driving trust, engagement, and positive perceptions across cultural contexts. This can be achieved through user-friendly interfaces, transparent performance metrics, such as real-time air quality feedback, and simplified interactions using dashboards or visual cues. Furthermore, contextual tailoring is essential. In countries where environmental values are stronger, such as in the UK, Portugal, and Greece, public messaging should emphasize the sustainability and climate co-benefits of IAQ technologies. Where hedonic motivation plays a role, such as in the UK and Sweden, user experience could be enhanced through enjoyable and rewarding interactions, such as integrating gamification and lifestyle features. Finally, building managers and policymakers should recognize that comfort is strongly tied to IAQ perception, particularly in public spaces where perceived air quality is often low. The results per country are displayed in Table 3.

5. Discussion and implications

5.1. Principal findings

Response efficacy and intuitiveness are the most important enablers of comfort provided by IAQMTs. Indicating the importance of effective management strategies for indoor air quality in improving the perception of IAQ and the perception of comfort in public indoor environments (Al horr et al., 2016; Saini et al., 2024) and the intuitiveness of these management technologies is essential for empowering users to interact with connected devices and systems (Cui et al., 2024). Hedonic

Table 3
Structural model results for each country (***p-value < 0.001; **p-value < 0.05; *p-value < 0.10).

Target variable	Independent variable	Germany	Greece	Ireland	Portugal	Spain	Sweden	UK
Indoor air quality perception	Hedonic motivation	0.167*	0.038	0.06	0.04	0.097**	0.084**	0.176***
	Convenience	−0.018	0.068	0.055	0.08	0.128*	−0.034	−0.165***
	Intuitiveness	0.261***	0.345***	0.480***	0.297***	0.314***	0.492***	0.395***
	Response efficacy	0.416***	0.319***	0.247***	0.424***	0.339***	0.327***	0.418***
	Privacy concern	0.032	0.001	−0.075	−0.028	−0.009	−0.05	0.001
	Information concern	−0.055	−0.122***	0.045	0.032	−0.032	0.021	−0.036
	Health consciousness	−0.007	0.035	0.023	−0.029	0.021	0.067	0.084
	Environmental consciousness	0.094	0.116**	0.104*	0.117***	0.098*	0.06	0.125**
Public environmental comfort	Hedonic motivation	0.088	0.085	0.087*	0.063	0.173***	0.063	0.153***
	Convenience	0.055	0.06	−0.029	−0.066	0.100*	0.07	0.046
	Intuitiveness	0.231***	0.195*	0.146**	0.158**	−0.001	0.104	0.087*
	Response efficacy	0.311***	0.130**	0.089	0.098	0.155***	0.136*	0.04
	Privacy concern	−0.096	0.013	−0.013	0.025	0.046	−0.049	0.076
	Information concern	0.037	0.028	−0.006	−0.057	−0.047	0.076	−0.071
	Health consciousness	−0.013	−0.029	−0.05	0.082*	0.002	0.083	0.033
	Environmental consciousness	−0.034	0.06	0.171***	0.014	0.077	−0.02	0.063
	Indoor air quality perception	0.232***	0.427***	0.534***	0.566***	0.502***	0.502***	0.532***

motivation also plays an important role, which reinforces a link between individuals having fun and enjoying their experience and an improvement in their health or well-being (Johnson et al., 2016; Y. Lin et al., 2018). Convenience is not an enabler of comfort provided by IAQMTs, which can be explained by the fact that while automation is more effective in improving IAQ, having personal control over environmental settings can significantly enhance occupants' IAQ satisfaction and comfort perceptions (Schweiker et al., 2020; Son et al., 2023). We have also established that a good IAQ perception can help individuals feel safer and more comfortable in public places with high foot traffic, as it is a place where individuals tend to perceive lower levels of perceived IAQ (Song and Kwan, 2023).

Information and privacy concerns do not inhibit the perceived comfort provided by IAQMTs. Although our findings are contrary to what was expected, literature on smart healthcare services found that loss of privacy had no direct impact on behavior, but impacted an individual's perceived trust (Liu and Tao, 2022). Furthermore, privacy might not be seen as an inhibitor of these types of technologies, as users might feel protected by policies and regulations like the GDPR, which has established a comprehensive framework that addresses key privacy principles such as transparency, data minimization, and accountability (Kitkowska et al., 2024). Environmental-conscious individuals, that is, individuals concerned with air pollution and its impact on the environment, are more likely to perceive better IAQ provided by IAQMTs. Previous studies have found that when individuals perceive high levels of air pollution, it strengthens their awareness of climate change, as both issues share similar causes and health implications (Sun et al., 2024). Individuals with higher health consciousness are more likely to perceive greater levels of comfort provided by IAQMTs, as they seek ways to manage their health proactively and make informed decisions, and are more aware of the health-improving benefits of these technologies (Cho et al., 2014).

5.2. Theoretical implications

This study contributes to the growing body of literature on IAQ management by integrating behavioral and technological perspectives to examine how individuals perceive comfort and air quality in environments equipped with IoT-based IAQMTs. While prior research has primarily focused on technical performance or health outcomes (Borah et al., 2024; Cheek et al., 2021), our findings emphasize the role of individual perception as a key participant in the success of IAQ interventions. By drawing on the dual-factor theory (DFT), this study extends theoretical understanding by showing how both enablers, such as hedonic motivation, intuitiveness, and response efficacy, and inhibitors like privacy and information concerns influence perceived comfort tied to IAQ, particularly in public indoor environments. While the DFT traditionally examines enablers and inhibitors of technology adoption (Das and Ramalingam, 2023), our model incorporates individual characteristics, specifically health and environmental consciousness, into the conceptual framework, and our findings underscore the significant role of personal characteristics in shaping perceptions related to IAQMTs.

Moreover, this research introduces and validates new reflective measurement scales for understudied constructs such as perceived comfort in public indoor environments and intuitiveness of IAQMTs. The generalizability of this model across multiple European countries also provides initial evidence of the robustness and cross-cultural relevance of these constructs, opening avenues for further user-centered research. By showing how certain enablers foster positive occupant perceptions, our research underscores the importance of designing IAQMTs that promote and meet individuals' management needs. IAQMTs should have intuitive, interactive, and adaptable interfaces, enabling users to feel that they can improve IAQ and create a comfortable, healthy, and sustainable indoor environment (Cui et al., 2024; Šujanová et al., 2019). This can inform future studies in environmental management, linking tangible IAQ improvements to behavioral sciences, where user perception is considered when designing these technologies and when managing indoor environments.

5.3. Practical implications

The findings of this study offer several practical insights for stakeholders such as building managers, policymakers, and technology developers, who can help bridge the gap between technical IAQ interventions and the behavioral factors that ultimately determine their success. This research is a step in understanding how specific factors drive comfort through IAQ management, offering insights on human interaction with the indoor built environment to generate positive occupant perceptions. Response efficacy emerged as an important enabler, highlighting that users want clear evidence that IAQ interventions effectively reduce pollutants and enhance comfort. Building managers and manufacturers should provide transparent metrics such as real-time pollutant levels and color-coded IAQ level indicators, so that occupants can see quantifiable proof of the system's impact (Francisco et al., 2018; Shoukry et al., 2024). It is also important to underscore that the perception of air freshness and cleanliness can help individuals feel safer and more comfortable in public places with high foot traffic (Gür, 2022; Zou et al., 2025). Therefore, IAQ improvement can feel especially important in more crowded environments.

The integration of intuitive elements is essential in enhancing user experience. By prioritizing user-centered design principles and intuitive interfaces, individuals will feel like these technologies can improve the IAQ and comfort indoors (Roofigari-Esfahan and Morshedzadeh, 2025). Features such as simple dashboards, minimal setup steps, and clear on-device prompts can empower occupants to engage with and trust the system's ability to improve indoor conditions (Dai et al., 2023). Furthermore, making IAQ solutions a fun and enjoyable experience is going to make users more likely to feel that IAQMTs are improving their comfort levels (Lee and Kim, 2020). Gamified elements, such as awarding "clean air points" for optimizing ventilation and other positive user experiences, can encourage occupants to actively participate in IAQ management (Neves et al., 2024). Although it should be noted that in Greece and Portugal, this is not the case.

The lack of impact of convenience brought by automation shows that giving occupants some degree of personal control with adjustable ventilation settings or user-specific preferences can play a significant role in occupant IAQ satisfaction (Kim et al., 2023; Son et al., 2023). Experts advocate for designing built environments that enhance well-being by accommodating individual preferences, enabling personalized control over environmental factors, and prioritizing human-centered experiences, creating adaptable spaces that actively support occupants' comfort, health, and satisfaction (Altomonte et al., 2020). Users' experience must be adaptive to individual preferences, ensuring that users find the technology genuinely helpful and easy to integrate into their lives (Cui et al., 2024).

Contrary to initial expectations, privacy and information concerns did not act as barriers, likely due to robust data protection regulations like GDPR in the European context. These legal safeguards reassure users by ensuring that IoT manufacturers and service providers implement robust measures to protect personal data, thereby fostering trust and facilitating the adoption of IoT systems without privacy concerns overshadowing the user experience (Kim et al., 2023; Prastyanti and Sharma, 2024). Isolated findings, such as the significant effect of information concern in Greece, suggest that in lower-trust contexts, clarity and credibility of information are essential. Additionally, our findings emphasize that individuals with heightened environmental and health consciousness are more likely to consider these technologies to improve IAQ and comfort outcomes. Therefore, communication strategies should emphasize the environmental and health benefits of IAQ management technologies. For instance, environmentally aware individuals are more aware of IAQ as both share similar causes and health implications, and this perception can lead to increased support for climate actions, particularly through behaviors aimed at avoiding pollution, such as purchasing air purifiers (Sun et al., 2024).

Finally, this research supports the broader policy direction of the European Union toward smart, sustainable buildings. Our findings reveal that comfort perception is strongly tied to IAQ perception in all national samples, reaffirming the need for technologies that are not only functional but also perceived to improve well-being. Integrating occupant-focused IAQ solutions aligns seamlessly with the EU's regulatory vision for a more sustainable and healthier built environment (European Commission, 2025; Verbeke et al., 2020). This should encourage building owners and managers to implement IoT solutions that improve occupant comfort and health. This can be done by ensuring the implementation of IAQMTs that meet individuals' management needs, which integrate intuitive, adaptable interfaces, and give occupants a sense of personalization or control over environmental parameters. Transparency should also be highlighted to make sure occupants know the effectiveness of IAQMTs.

5.4. Limitations and future research

We acknowledge some limitations in our study. First, we conducted a cross-sectional study. Therefore, future research may enhance the validity and generalization of our findings through longitudinal research. Second, the research model may not have included all potential enablers and inhibitors. Consequently, in future research, it would be interesting to investigate additional variables related to IAQ management and its implications. Furthermore, examining potential moderation and mediating effects could offer a more comprehensive understanding of the mechanisms underlying users' perceptions. Finally, considering the context-specific nature of our self-developed variables, testing them across diverse samples and settings could further validate their applicability.

6. Conclusions

This study demonstrates how technology influences perceived comfort in indoor environments and successfully adapts the dual-factor theory to understand IAQ perception and comfort. This can inform future studies in environmental management, linking tangible IAQ improvements to behavioral sciences, where user perception is considered when designing these technologies and when managing indoor environments. IAQMTs should have intuitive, interactive, and adaptable interfaces, enabling users to feel that they can improve IAQ and create a comfortable, healthy, and sustainable indoor environment. Contrary to what other studies suggest, information and privacy concerns do not inhibit individuals' perceptions. However, addressing these concerns remains important for user trust and to foster the use of IAQ solutions. Individuals' characteristics specifically related to concerns with health and air pollution, and environmental impacts, proved to be important in influencing individuals' perceptions. By integrating these insights, practitioners can design and implement IAQ management strategies that not only curb pollutant levels but also align with occupants' perceptions, motivations, and comfort needs. By integrating the subjective experiences of occupants and aligning IAQ solutions with EU-level directives, policymakers, building managers, and technology developers can collectively foster healthier, more sustainable, and more comfortable indoor spaces across Europe.

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CRediT authorship contribution statement

Inês Veiga: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tiago Oliveira:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Mijail Naranjo-Zolotov:** Writing – review & editing, Validation, Supervision. **Ricardo Martins:** Writing – review & editing, Validation, Supervision. **Stylianos Karatzas:** Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109690.

Data availability

Data will be made available on request.

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