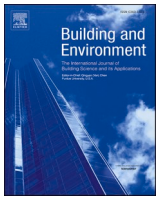
Building and Environment 270 (2025) 112526

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



Gamification for air quality education: A systematic literature review

Abdollah Baghaei Daemei [a,*], Ruggiero Lovreglio [a,*], Zhenan Feng [a], Daniel Paes [a], Clayton Miller [b]

[a] School of Built Environment, Massey University, Auckland, New Zealand
[b] Department of the Built Environment, National University of Singapore, Singapore

ARTICLE INFO

Keywords:
Gamification
Serious games
Game mechanics
Education
Public awareness
Indoor air quality
Outdoor air pollution
Mold assessment
Asthma management
Taxonomy

ABSTRACT

Air quality is crucial to our health and well-being, as poor air quality can lead to serious health problems such as asthma, allergies, and other respiratory conditions. Educating people about air quality is key to improving awareness and taking action to reduce its negative effects. Gamification offers a creative and engaging way to deliver educational content by incorporating game elements into the learning experience. However, despite its potential, there has been no review of how gamification has been used for air quality education. Thus, this review aims to fill that gap by systematically examining how gamification is applied to air quality education in the built environment. We explored a range of games and applications used to educate the public on air quality. To guide our analysis, we used the Octalysis framework, which focuses on game elements that motivate and engage users. Following the PRISMA guidelines for systematic reviews, we identified 19 relevant papers published between 2009 and 2023. From these, we developed 8 research questions to guide the review process and analyzed the game elements using the Octalysis framework. Our findings show that most studies focus on residential buildings, with a key focus on raising awareness of the health impacts of air pollution and managing asthma. Notably, many of these studies target children, who are more vulnerable to air pollution. We also introduce the first taxonomy for gamification in air quality education, providing a clear structure for future game development in this area. Finally, the review highlights the need to explore other educational topics that could benefit from gamification, and how this approach could improve both indoor and urban air quality, as well as reduce energy consumption.

Acronyms

IAQ	Indoor Air Quality
OAP	Outdoor Air Pollution
CD	Core Drive
CO_2	Carbon Dioxide
VOC	Volatile Organic Compounds
CO	Carbon Monoxide
PM	Particulate Matter
NO_2	Nitrogen Dioxide
UVI	Ultraviolet Index
O_3	Ozone
NH_3	Ammonia
TVOC	Total Volatile Organic Compounds

1. Introduction

In our rapidly evolving world, poor indoor and urban air quality and pollution have risen to the forefront of environmental concern, affecting the design of the future built environment [1,2]. This nationwide issue poses significant threats to public health indoors and outdoors [3]. Being exposed to elevated air pollution levels can lead to various adverse health consequences, such as respiratory infections, heart problems, and lung cancer, which causes almost seven million deaths worldwide per annum [4,5]. The COVID-19 outbreak contributed to the importance of indoor air quality in buildings and its impact on occupants' health [6]. High concentrations of CO_2 in indoor spaces can impact personal factors such as human productivity and increased tiredness levels [7,8]. Low air quality and exposure to air pollutants can have health impacts in both the short and long term, with particularly severe consequences for individuals who are already unwell [9]. Vulnerable groups, including children, pregnant women, the elderly, and those with limited financial

* Corresponding authors.
E-mail address: abaghaei@massey.ac.nz (A.B. Daemei).

https://doi.org/10.1016/j.buildenv.2025.112526
Received 6 November 2024; Received in revised form 17 December 2024; Accepted 2 January 2025
Available online 3 January 2025

resources, are at a heightened risk [10]. Additionally, it irritates the nose, throat, eyes, and skin, causing headaches, dizziness, or nausea [11,12]. This emphasises the need for holistic global solutions to overcome such issues [13,14]. The repercussions of air pollution extend beyond immediate discomfort. An increasing amount of evidence indicates that air pollution can also have detrimental effects on the brain [15,16].

According to a report published by Underwood [17], dirty air causes cognitive ageing and potentially elevates the risk of Alzheimer's disease and other types of dementia. In another study, Wang [18] provided new evidence demonstrating the link between air pollution, stroke, and dementia. Thus, educating individuals about the sources and consequences of air pollution is critical, equipping them with educational content about air quality to the utmost [19]. Such knowledge can help people change their behaviour, make informed decisions, and promote overall health and well-being [20,21]. The necessity to educate the public about the sources and consequences of air pollution is closely tied to the concept of Environmental Health Literacy [22]. As the National Institute of Environmental Health Sciences highlighted in 2014 [23] Environmental Health Literacy is an evolving concept integrating theories from risk communication, environmental health science, behavioural science, evaluation, communications, public health, and the social sciences [24].

One promising avenue for delivering engaging and effective air quality education is through gamification [25,26]. Gamification applies game elements and principles in non-game contexts [27,28]. Integrating educational content on air quality into interactive and immersive games can enhance people's awareness [29]. This approach utilises the enjoyment and motivational aspects of games to encourage positive changes in behaviour [30,31]. Studies show people are more engaged and productive in gaming activities [32]. Kim [33] stated that games can boost people's performance in ways that real-world scenarios might not achieve. Similarly, many studies have reported positive educational outcomes in the gamification [34–36]. As such, gamification can play a crucial role in air quality education. It can help users understand how they can play a role in enhancing air quality and the impact of their decisions on other factors, such as thermal comfort and energy consumption.

Despite preliminary research on the topic of gamification for air quality education, the current understanding of utilizing gamification techniques to educate the public about air quality (indoors and outdoors) lacks a comprehensive overview. Although some papers exist on the topic, there has not been a systematic review that consolidates and analyses the state-of-the-art approaches. Even though scattered research articles may touch upon aspects of gamification and air quality education, a comprehensive review is necessary to synthesize existing knowledge, identify trends, assess effectiveness, and uncover gaps in research. Such a review would provide valuable insights for researchers, policymakers, and practitioners seeking to leverage gamification as a tool for public education on air quality.

While evidence from other fields may suggest the potential benefits of gamification, particularly in engaging learners and promoting behaviour change, no studies have directly compared gamification's impact to traditional methods regarding knowledge acquisition, retention, and behavioural changes specifically related to air quality education. For example, various studies have investigated the effectiveness of digital and innovative methods (i.e., gamification) in training, including for earthquake preparedness [37–39], safety training [40,41], construction sites [42,43], hazard detection [44–46], risk management [47], and other general topics in the built environment [48–50].

This study reviews the application of gamification in air quality education by identifying various delivery methods and game elements used for educational purposes. The term `game element' is called `game mechanics' or `techniques.' In this study, the term game elements will be used. A systematic literature review was conducted to achieve this aim, assessing nineteen papers published between 2009 and 2023. This work involved analysing the context and methods of gamification applications. The Octalysis framework developed by [51] has been used to assess the gamification strategies adopted in these studies, marking this work the first instance of the Octalysis framework application in air quality educational research—additionally, the research aimed to identify specific game elements that effectively stimulate individual motivation and engagement.

This review study represents a new milestone in air quality education research, contributing new insights into how gamification and game elements have been adopted for air quality education and new ideas on how gamification can be applied in the future. Although various studies have assessed the effectiveness of serious games and gamification in the built environment, the current state of gamification in air quality education remains largely unknown. More importantly, there is no existing taxonomy for gamification or serious games specifically related to air quality education. This work proposes the first such taxonomy, providing a structured framework for the development and analysis of gamified applications and serious games in this field.

2. Background

This section provides a brief background about gamification and game elements. Additionally, the types of games are classified. Subsequently, the differences between serious and non-serious games are distinguished, along with categorizations into non-digital and digital games, and a summary of immersive and non-immersive games is provided (see Section 2.1 for more details). Furthermore, critical issues of Indoor Air Quality (IAQ) and Outdoor Air Pollution (OAP) are explored in Section 2.2, emphasizing their significant impact on public health and the environment. Throughout this work, referencing 'air quality' encompasses both IAQ and OAP unless explicitly specified otherwise.

2.1. Gamification

Gamification integrates gaming elements, principles, and mechanics into non-game contexts to engage and motivate individuals [52]. It involves applying elements or game elements commonly found in games, such as competition, points, rewards, badges, challenges, and interactive storytelling, to activities that typically do not involve gameplay [53]. Gamification enhances user engagement, increases motivation, and drives desired behaviours. Gamification makes tasks more enjoyable, boosts participation, and achieves specific objectives [54]. It uses the psychological aspects that make games compelling, such as the desire for achievement, competition, and the enjoyment of challenges [32]. Game elements refer to the individual components or features that make up a game, including badges, avatars, points, etc. These elements contribute to the overall gaming experience, providing interactive and visual aspects that engage players [55].

Game designers can use various game elements to create challenges, objectives, and the overall structure of a game. These elements work together to create a unique and engaging gameplay experience. Game designers must carefully balance and iterate these elements to ensure the gaming experience is enjoyable, challenging, and aligned with the intended player experience [56]. In general, games are classified into serious games and non-serious games. Serious games are primarily designed for educational, training, simulation, or informational purposes rather than pure entertainment. Serious games often use gaming elements to make learning or training more engaging and effective [57]. The main objective of serious games is to impart knowledge, teach specific skills, or simulate real-world scenarios [58,59]. In contrast, non-serious games, also known as entertainment or recreational games, are designed primarily for entertainment purposes [60]. These games focus on providing an enjoyable experience without specifically emphasising educational or training objectives [61].

Serious games also can be categorised into non-digital and digital games. Non-digital games are traditional games that do not involve electronic or digital technology. These games are played using physical components, such as cards, boards, dice, or other tangible items, and

they do not rely on computerised or electronic interfaces [62,63]. Digital games can be further divided into immersive and non-immersive. Immersive games are designed to deeply engage players in a virtual environment, creating a sense of presence and involvement, aiming to make players feel like they are part of the game world, blurring the line between the virtual and real [64]. Virtual reality and Augmented Reality (AR) technologies are commonly used to create immersive gaming experiences [65]. Non-immersive games may not employ advanced technologies to create a deeply engaging virtual environment. These games still provide entertainment but may not focus on creating a sense of high immersion [66]. In non-immersive games, the player's awareness of the real-world environment may be more pronounced, and the gameplay may not strive to create a fully immersive experience [67].

2.2. Air quality and education

Generically, air quality refers to the condition of the air within our surroundings, describing how polluted the environment is [68]. It is a multidimensional concept that assesses the cleanliness of the air people breathe and its impact on their health, the environment, and overall well-being [69]. Monitoring air quality indoors and outdoors involves evaluating the concentration of pollutants such as carbon dioxide, carbon monoxide, nitrogen dioxide, particulate matter, ozone, volatile organic compounds, etc. On the one hand, the goal is to maintain air quality within acceptable standards, as indicated by the Air Quality Index [30], to safeguard human health and the ecosystem [70]. Also, raising public awareness should be considered to avoid the threat of toxic air.

Educating individuals about air quality is paramount due to its significant and far-reaching implications on public health and the environment [71]. Also, they can actively participate in efforts to control and manage air pollution [72]. Many people are unaware of the invisible threats in the air they breathe, and raising awareness is crucial for making informed decisions and adapting behaviour [73]. If people become more aware of the importance of air pollution, it is more likely to prompt positive changes in both individual behaviour and public policies [74]. This increased awareness has the potential to drive actions to mitigate pollution, resulting in a cleaner environment and a healthier population [75,76]. Therefore, boosting education and training and increasing public awareness can lead the public to achieve goals related to environmental pollution [11].

Moreover, well-informed individuals are more likely to advocate for policies and practices contributing to cleaner air. This collective effort on a global scale can lead to reduced health risks, including lower rates of respiratory conditions such as asthma, improved overall well-being, and a healthier future for communities worldwide [77]. To this end, a practical educational approach to air quality is needed. An innovative approach gaining momentum is the incorporation of gamification into air quality education. Gamification transforms learning about air quality into an engaging and interactive experience by applying game elements and offering various features such as real-time data collection [78]. Through gamified applications and platforms, individuals can participate in challenges, quizzes, and simulations that simulate real-world scenarios related to air quality.

To date, a comprehensive exploration of the air quality educational applications of gamification in the context of built environment is currently lacking in the existing literature. This work aims to fill this research gap by providing a systematic literature review to explore existing gamification applications in air quality education.

3. Material and methods

This section outlines the methods employed in this work. In this study, a systematic literature review is used to identify relevant articles in the literature. This systematic approach allows researchers to rigorously identify, select, and synthesize relevant studies from various sources, ensuring a thorough and unbiased review of the existing literature [79]. As such, this study utilized the step-by-step approach provided by Khan [80] to identify the eligible articles. This approach is designed to assess the relevance of identified work with the research questions and reduce the number of papers to analyze. The steps used in this review are:

i) Defining research questions;
ii) Identifying the relevant work;
iii) Summarising the evidence;
iv) Interpreting the findings;

3.1. Defining research questions

This research aims to provide insight into gamification applications oriented toward air quality. The following research questions (Q1 to Q8) were framed to seek the diverse aspects of gamification in air quality education. These research questions are inspired by a general classification of serious games developed by [81]. Further, the questions align with the previous systematic review conducted by [82], which used a similar approach. The research questions are presented as follow:

Q1: What was the primary context of the game?
Q2: What was the learning objective of the game?
Q3: What was the profile of the trainees, and what was the sample size?
Q4: What game elements were applied?
Q5: What types of delivery methods and applications were used?
Q6: What were the reported results?
Q7: What were the challenges of the delivery method and applications?
Q8: What psychological and learning theories or models were employed in the design of gamified air quality applications?

3.2. Identifying the relevant works

This study followed the PRISMA Statement to identify relevant articles (Fig. 1). Relevant articles were retrieved from multiple databases, including Scopus, Web of Science (WOS), and IEEE Xplore. These databases were selected as the preferred database, as they have more global content than other providers while maintaining a selective approach [83–86]. This exploration was conducted on 17th of October 2024 using the keyword string: gamif* OR ``serious gam*'' OR ``game-based'' OR ``interactive learning'' AND ``air quality''. No further filters of the database have been allocated in the search process (e.g., language and subject area). The '*' (asterisk) operator was used in the keyword to include all terms relating to gamification, such as gamify, gamifying, gameful, gamification, and gaming. After removing 16 duplicates from the three databases, an initial screening was implemented. After that, a secondary screening was conducted involving reading the full text to assess the eligibility of the studies.

The secondary screening concluded 12 eligible studies. After that, backwards and forward snowballing was applied to these eligible articles. Backward snowballing consisted of tracing the references cited in foundational research papers, allowing us to explore the historical context of the topic and identify additional studies that significantly contributed to the field [87]. Furthermore, forward snowballing was utilised to identify more recent studies that cited pivotal research papers [88]. Another seven eligible studies were discovered through snowballing. Consequently, 19 eligible articles were included in this systematic literature review [86,89–106]. Table 1 illustrates the inclusion and exclusion eligibility criteria for selecting the literature studies. Further, Appendix A provides a summary of the eligibility articles.

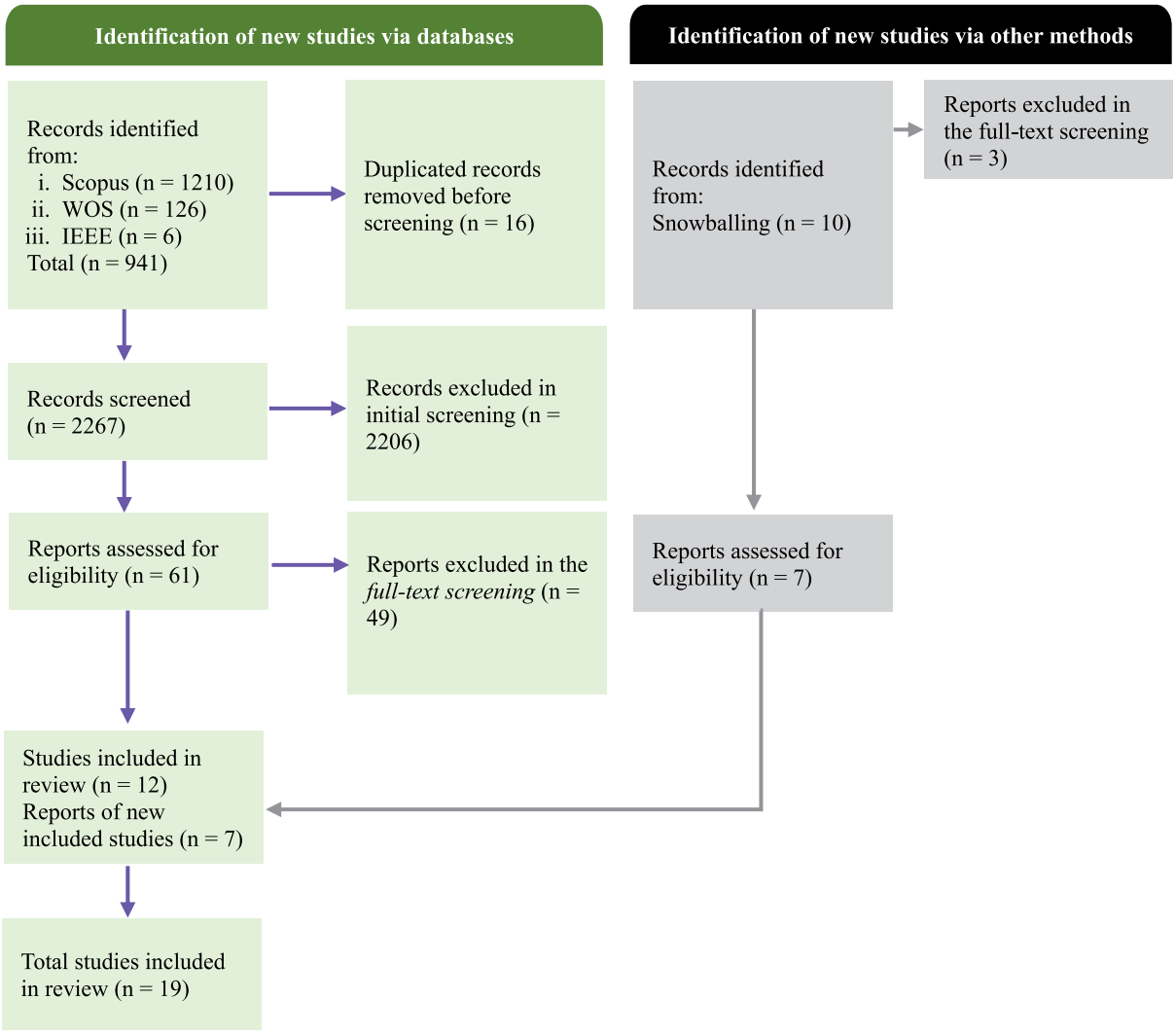


Fig. 1. PRISMA flow diagram and the process of identifying the relevant works.

3.3. Analysis approach

One of our research questions (Q4) aims to assess the game elements adopted in the proposed air quality applications. To achieve this, we utilized the Octalysis framework, a well-established Gamification Design Framework developed by Chou [51]. The Octalysis framework breaks down into eight Core Drives (CDs), represented in an octagon shape as shown in Fig. 2 (hence the name ``Octalysis''). Each CD also incorporates various game elements (as they can be seen in the corners of the Octalysis). These elements are the individual components or features within a game that contribute to the overall gaming experience [107]. For instance, points are a game element of CD 2. These CDs are the fundamental psychological motivations that drive individuals to engage in a particular activity or game.

The Octalysis framework has been widely used in various fields, including marketing, education, and product design, to enhance user engagement and drive desired behaviours [108,109]. As such, it represents a suitable tool for analyzing the gamification solution adopted in the selected papers for air quality education. Rather than using the Octalysis to design game elements directly, we employed the Octalysis framework as a structured analytical model to systematically identify, categorize, and understand the game elements present in prior studies to response Q4.

4. Results

In this systematic literature review, a total of nineteen papers published between 2009 and 2023 were identified, comprising eleven journal articles, six conference papers, one book chapter, and one master's thesis. A summary of all the eligible articles reviewed in this study is provided in Appendix A (Summary of the eligible articles). Fig. 3 illustrates the number of publications and types of scholarly outputs per annum. The Figure shows a substantial incrase in the number of applications in 2020 and 2021. This trend likely corresponds to the rise in research and publications during the COVID-19 pandemic, as the global situation heightened interest and urgency in health-related topics, including air quality education through gamification [110,111].

4.1. Primary contexts of the games

This section explores the potential information concerning the first research question in this study, focusing on the primary contexts of the games discussed in the literature. The primary focus of the games revolved around diverse facets of air pollution, focusing on IAQ, OAP, and both. The findings show that three types of built environments have been investigated, including classrooms (one paper), residential buildings (seven papers), and general environments (eleven papers). The general environment implies that the study did not mention any specific case study, space, or building typology. Further, most studies used real-

Table 1
Eligibility criteria for the screening stages.

Stages	Criteria	Decision
Searching	Peer-reviewed studies such as journal articles, conference papers, and book chapters.	Inclusion
	When the specified keywords are present either in the entirety or at least within the paper's title, keywords, or abstract.	Inclusion
	In case of any duplication among the identified studies.	Exclusion
	Studies that are books, review papers, and meta-data.	Exclusion
Title and abstract screening	Studies present sufficient information on the gamification of either indoor or outdoor air quality education.	Inclusion
	Studies that analyzed or tested any education methods, including digital (e.g. mobile apps or video games) and non-digital (e.g. classroom-based activities or board games).	Inclusion
	The main focus was not on air quality education (e.g., energy efficiency, thermal comfort, etc.).	Exclusion
Full-text screening	Studies that only propose the use of gamification without any experimental testing.	Exclusion
	Studies that do not incorporate gamification elements in any form (e.g., points, rewards, challenges, or interactive play) as part of their methods.	Exclusion
	The studies have no information regarding the learners or testing subjects (characteristics and sample size).	Exclusion

time data collection, integrating with the application which can collect various environmental parameters, namely temperature, CO_2, VOCs (Volatile Organic Compounds), CO, air pressure, PM10, PM2.5, $N0_2$, formaldehyde, UVI (Ultraviolet Index), O_3 (ozone), PM1.0, PM4.0, PM1, smoke, benzene, sulphide, and alcohol. Detailed information on the built environment context and the IAQ and OAP parameters is presented in Table 2.

Fig. 4 provides further details about the relationship between primary contexts and the number of publications per annum. Most of the articles investigated IAQ as the leading environmental context.

4.2. Learning objective of the games

This section addresses the study's second research question regarding the primary learning objectives of the games, which are categorized into two main groups: asthma management (26 %, four studies) and awareness and perception (74 %, fifteen studies). Fig. 5 illustrates the relationship between these key contexts and the number of publications per year. The asthma management objective focuses on helping users control and alleviate asthma symptoms by fostering daily asthma management behaviours. This is achieved by highlighting the link between air quality and respiratory health [94,104]. Key strategies include supporting users with IAQ monitoring [101] and providing reminders to ensure adherence to prescribed asthma management measures [102]. The awareness and perception objective aims to enhance users' understanding of air pollution and its impacts. This involves raising awareness of pollutant exposure, promoting knowledge of associated health effects, and emphasizing the significance of IAQ. The objectives also seek to foster social responsibility, encourage behavioural changes, and promote the adoption of protective measures. Collectively, these initiatives aim to create well-informed and engaged users who are better equipped to address the challenges posed by air pollution.

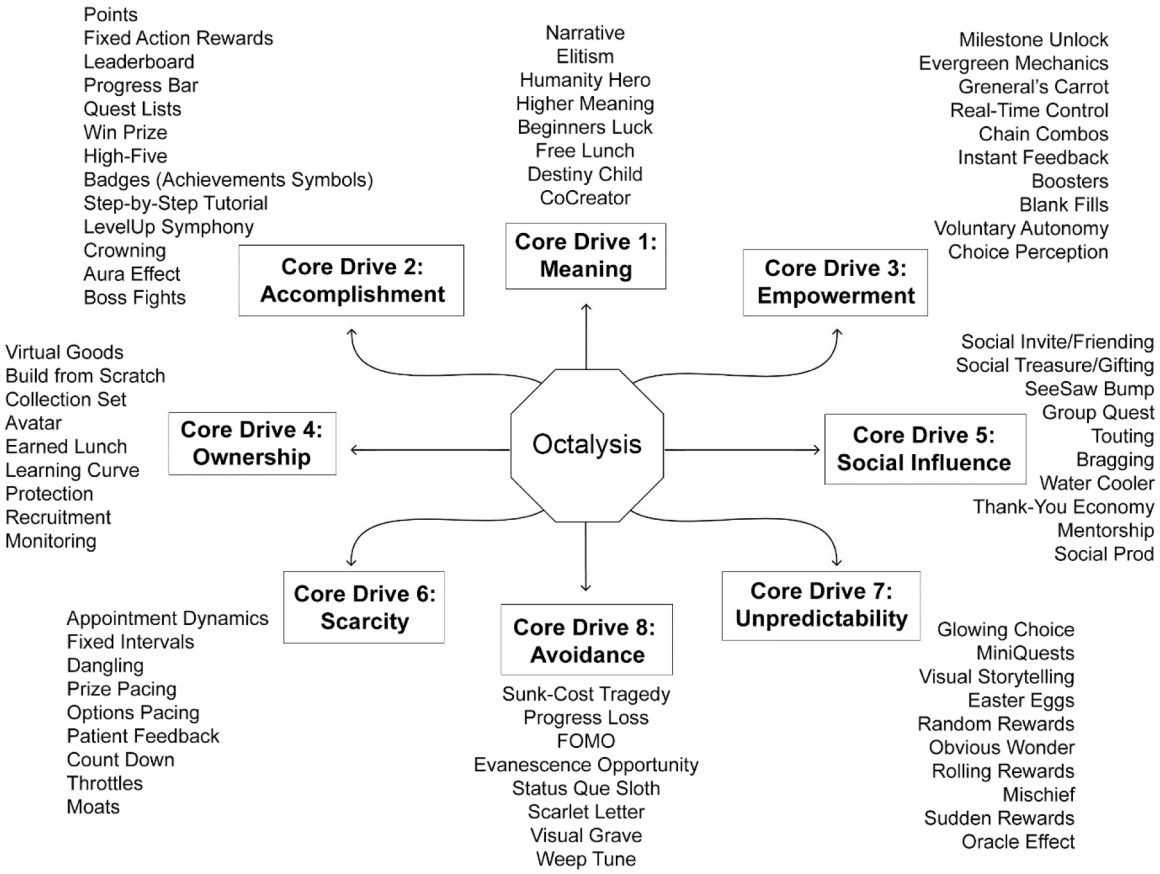


Fig. 2. Gamification Design Framework, Octalysis, modified from [51].

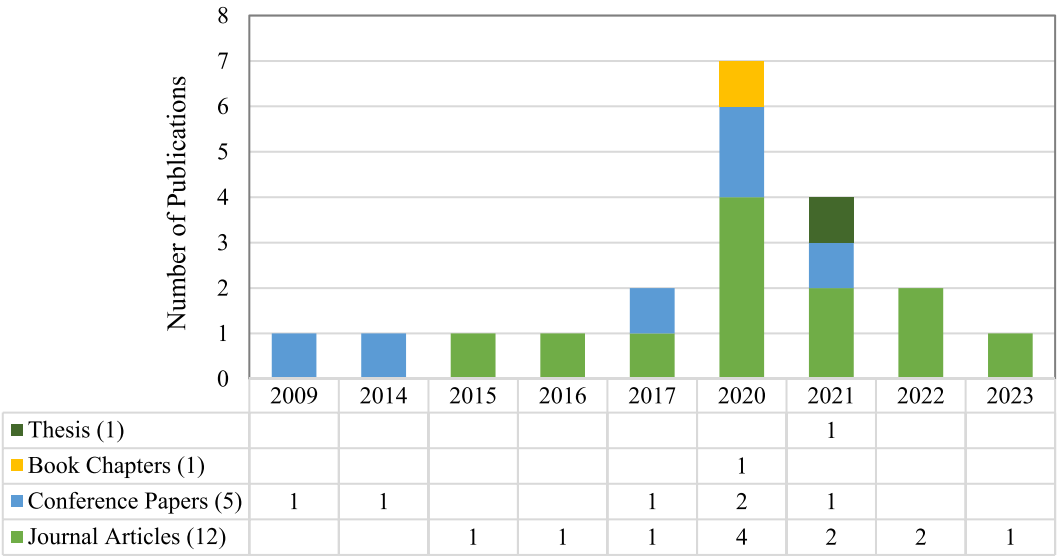


Fig. 3. Summary of the eligible articles' source output and the number of associated publications.

Table 2
Details of the main context of the games and the collected environmental parameters.

Publications	Indoor/ outdoor	Built environment	Real-time IAQ and OAP elements
[89]	Indoor	Classroom	Temperature, CO_2, and VOCs*
[90]	Both	General	CO, air pressure, temperature
[91]	Indoor	General	Temperature, air pressure, humidity
[92]	Both	General	N/A
[93]	Indoor	Residential	PM10, PM2.5, VOCs, N02, CO
[94]	Indoor	Residential	N/A
[95]	Outdoor	General	Temperature, humidity, PM1.0, PM2.5, PM10, formaldehyde, UVI
[86]	Outdoor	General- Lisbon's Downtown (virtual environment replication)	NO_2, O_3, PM2.5, PM10
[96]	Indoor	General	PM1.0, PM2.5, PM4.0, PM10
[97]	Outdoor	General	N/A
[106]	Both	General	N/A
[98]	Both	General	PM1, PM2.5, PM10
[99]	Indoor	General	CO_2, NOX, NH_3, smoke, benzene, sulphide, alcohol
[100]	N/A	General-Virtual environment replication	N/A
[101]	Indoor	Residential	PM2.5, CO, CO_2, TVOC, NO_2
[102]	Indoor	Residential	PM2.5, CO_2, NO_2
[103]	Indoor	Residential	PM2.5, CO, CO_2, TVOC, NO_2
[104]	Indoor	Residential	PM2.5, CO, CO_2, TVOC, NO_2
[105]	Indoor	Residential	CO, NO_2, PM1, PM2.5, PM10

* This paper goes beyond measuring air quality parameters, including light and noise.

4.3. Profile of the trainees and the sample size

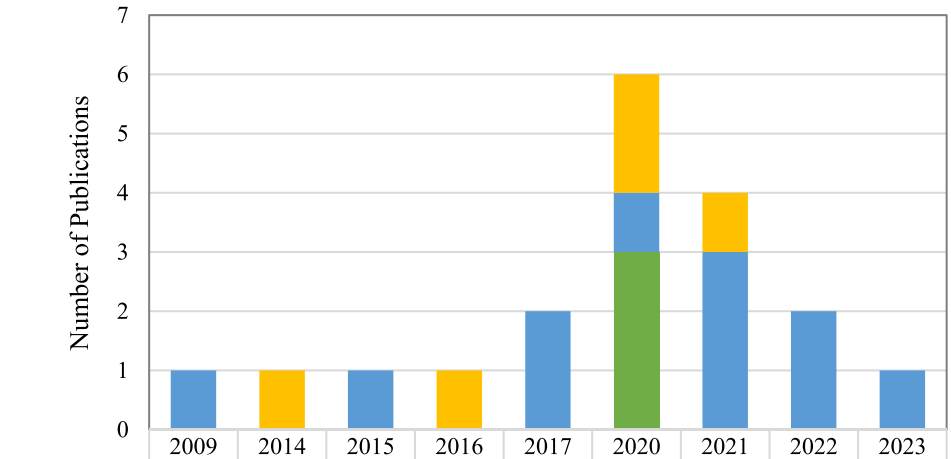
This section provides possible results to answer question 3 on the profile of the trainees. The gamification applications identified in this review were developed and tested for three generic groups of trainees, namely i) adults aged from eighteen to seventy-five, ii) teenagers aged from thirteen to seventeen, and iii) children below twelve years old. Fig. 6 represents the sample size distribution of the trainees involved in testing the gamification solutions in the selected works. Based on the findings, adults include professional employees and bachelor students, while teenagers comprise individuals from high school and senior high school. Children predominantly consist of elementary school students. Additional details about trainees' profiles can be found in Figs. 6 and 7.

4.4. The applied game elements

According to the fourth research question in this work, this section delves into the applied game mechanics in the literature. In the analysis of eligible articles, 16 distinct game elements were identified. Each element is associated with reference game elements within different CDs (Table 3). Labels A to P were assigned to correlate with each game element to facilitate reference and categorisation. For instance, Pokric [91] employed three game elements, namely 'scores, points and awards', 'choosing an avatar', and 'leaderboard'. Each game element is associated with reference game elements and labels: E – 'points', K – 'avatar', and F – 'leaderboard'. In some cases, the authors mentioned the game elements not associated with the reference game elements. Consequently, they were ravelled as Not Available (N/A). Relvas [100] used a game element entitled 'Main Character Explains to the Player and Dialogue'. In this case, this game element conveys two meanings. Therefore, two reference game elements were considered for it, which are 'Narratives' and 'Virtual Storytelling'. Varnavsky [97] did not clarify the game elements they utilised in their game. Hence, it was coded as Not Clarified (N/C). In Table 3, only the game elements found within the eligible papers were listed, not the complete group of game elements mentioned in the Gamification Design Framework (see Fig. 2 for further details about the game element). The Appendix B presents a definition of each game element and provides quotes from the original reference.

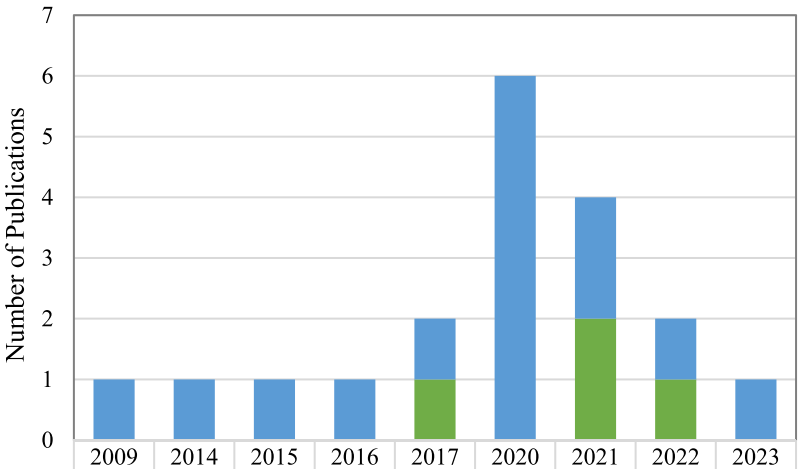
4.5. Types of delivery methods and applications

This section provides answers for the question 5 of this work on the delivery methods. Various methods and applications have been utilised to gamify air quality education. This review shows that most studies applied digital games. These games were mainly available on three main technologies, such as smartphones or tablets, as evidenced by the selected works. Also, laptops, PCs, and AR have been used to deliver the games. Also, two studies were categorised as 'Others'. Fig. 8 illustrates



	2009	2014	2015	2016	2017	2020	2021	2022	2023
Both (5)		1		1		2	1		
Indoor (11)	1		1		2	1	3	2	1
Outdoor (3)						3			

Fig. 4. Summary of the primary contexts of the eligible articles.



	2009	2014	2015	2016	2017	2020	2021	2022	2023
Raising Awareness (15)	1	1	1	1	1	6	2	1	1
Asthma Management (4)					1		2	1	

Fig. 5. Summary of the primary contexts of the eligible articles.

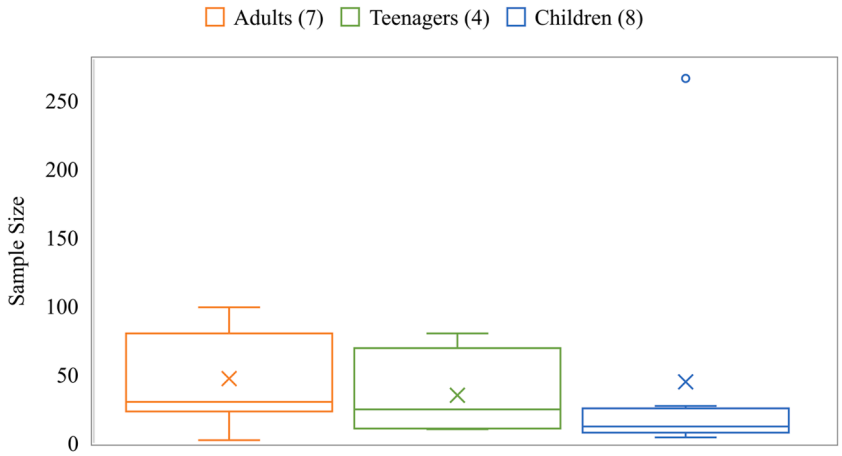


Fig. 6. Sample size distribution of the selected works.

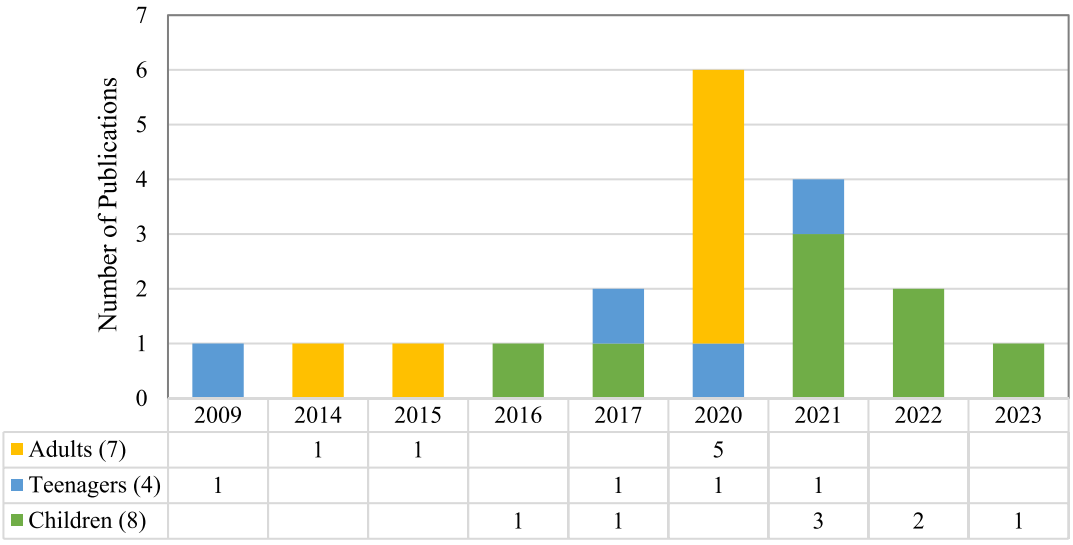


Fig. 7. Trainees' profile.

these methods by year.

The studies identified 2D and 3D games, played on smartphones/tablets or PCs/laptops. Some games were further integrated with activities, such as real-time air quality monitoring devices, and interactive quizzes and offline questionnaires combined with air quality sensors. Other methods, like cartoons and videogames, were also used. Another activity was the bicycle crowdsensing system, where users contribute data on cycling routes and environmental factors via mobile devices. AR integration appeared in four studies. For example, AR was used to place 3D objects in real-time video, enhancing immersion, and Unity with Vuforia was employed to create an AR app featuring a virtual character with sensor data represented by health and hunger states. Additionally, AR was used to visualize environmental data for education, and in one study, children interacted with virtual and real-world elements to make invisible information accessible. However, none of the studies utilized head-mounted displays or immersive virtual reality solutions. Table 4 represents the usage of each tool or activity in the related game/environment type.

4.6. Reported findings

Based on the question six in this study, the reported findings were classified into three groups: i) user engagement and feedback, ii) educational impact and awareness, and iii) perception and willingness. The reviewed studies present a positive outlook on user engagement within various applications. Niemeyer [89] and Bosello [95] reported overall positive feedback, underscoring high user engagement. Thomson [93] found that users, particularly children, experienced improved engagement and considered the game fun and helpful. Teles [86] observed high usage success rates, satisfactory task completion times, and positive user experiences. Campana [96] confirmed using smartphone environmental applications could increase trainees' social responsibility. They also concluded that the game increase curiosity and users' engagement. Varnavsky [97] noted that smartphone environmental applications contributed to heightened social responsibility, reflecting an active user participation trend. However, Kim [104] observed that while the graphical interface of their game received positive initial impressions, trainees reduced app use due to a perceived lack of interactivity and fun, highlighting areas for improvement. Fernandes [105] reported a significant improvement in knowledge (about 50 %) and positive assessments of satisfaction, usability, and opinions. Mahajan [98] noted overall positive user feedback regarding the tools, highlighting raised awareness and engaging user experiences.

Regarding educational impact and awareness, Leonardi [90] reported an increase in curiosity, leading to heightened motivation and awareness among citizens, indicating a positive educational impact. Pokric [91] stated that trainees found the game entertaining and the content provided was educational. Carducci [92] found that video games designed for children were useful, simple, and fun. In this study, trainees demonstrated noteworthy enhancements in learning outcomes by engaging in the videogame-based learning activity, including leaflets and storyboards. Statistical analysis revealed a significant knowledge increase among individual responses ($p < 0.05$). Delmas [106] observed that a positive user experience increased users' perception of air pollution.

Regarding perception and willingness, the reviewed studies also revealed varying aspects of trainees' perception and improvement needs in the context of air quality applications. Ling [99] reported that 60 % of trainees expressed willingness to use the application, indicating a positive overall perception and readiness to engage. Shabanabegum [101] identified limited knowledge among children regarding Indoor Air Pollution (IAP) and its impact on asthma, suggesting the imperative for educational improvement. Kim and Sohanchyk [103] noted positive initial interaction and increased parental involvement, signifying active parental and community engagement. Lastly, Relvas [100] reported a significant improvement in children's perception after the post-assessment, indicating positive changes in understanding. These studies underscore the effectiveness of innovative applications and tools in fostering air quality awareness, education, and engagement.

4.7. Challenge of the delivery method or application

Question seven of this work sought for any challenge of the applications reported in the literature. Some papers mentioned that they faced some challenges. For example, Pokric [91] reported encountering issues and highlighted the need for additional tutorials based on user feedback. Teles [86] criticised the application for lacking a rich narrative and having a poorly designed interface. Thomson [93] faced challenges due to the use of low-cost tethered devices, specifically impacting certain gameplay features. They used the Dylos air quality monitor, which relies on a wall outlet for power and a tethered 9-pin serial to full USB connection to the tablet. Grossman [94] encountered design limitations, including issues with the positioning and visibility of the flashing light indicator due to the opacity of the plastic shell of the dose counter. The dose counter, integrated with the game, had some issues, including a lack of sturdiness and functional limitations.

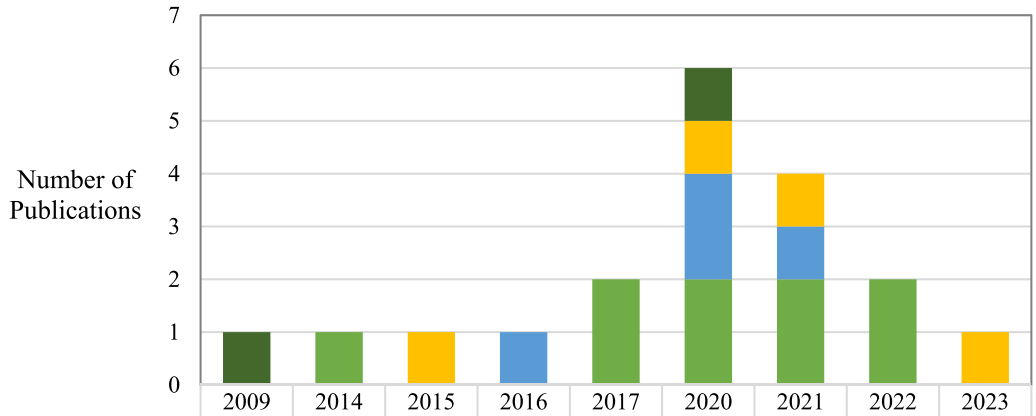
Table 3
The game elements translator.

Sources	Retrieved Game Elements	IDs		Reference Game Elements, developed by Chou [51]																
				CD1	CD2							CD3			CD4	CD5		CD7	CD8
				A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
				Narratives	LevelUp	Quest Lists	Step-by-Step Tutorial	Points	Leaderboard	Progress Bar	Win Prize	Instant Feedback	Choice Perception	Boosters	Avatar	Group Quest	Social Invite/Friending	Visual Storytelling	Progress Loss
[89]	Various Roles and Teams	3	M													■			
	Social Interactions		N														■		
	Difference in-Game Activities		N/C																
[90]	Real-time Feedback	1	H									■							
[91]	Scores, Points and Awards	3	E					■											
	Choosing an Avatar		K												■				
	Leaderboard		F						■										
[92]	Storyboard	5	A	■															
	Choose a Player (Boy or Girl)		L												■				
	Multiple Levels		B		■														
	Score		E					■											
	Score Reduction		P																■
[93]	Reminders	9	N/C																
	Feedback		H									■							
	Personalised Character, picks a name and avatar		K												■				
	Rewards and Prize		E					■											
	Task Completion and Daily Missions		C			■													
	Answering Questions		N/C																
	Secret Code		J											■					
	Space Locker		N/C																
	Take Photos for Postcards		N/C																
[94]	Customizable Avatar	11	K												■				
	Scorecard		E					■											
	Monetary Award		G								■								
	Reminder		N/C																
	Milestone		N/C																
	Objective		C			■													

(*continued on next page*)

Table 3 (*continued*)

	Dialog Box		N/C																
	Rules		N/C																
	Punishment		P																
	View Their Counterparts' Score		N/C																
	Immediate Feedback		H																
[95]	Motivations	3	N/C																
	Achievements, Level and Experience		B																
	Registration and Login		N/C																
[86]	Sitting on a bus (passenger)	6	N/C																
	Driving different buses		I																
	Tasks		C																
	Tutorials and help		D																
	Two driving modes		N/C																
	Teleport option		N/C																
[96]	Filter Options	5	N/C																
	Information Button		N/C																
	Particles Scale and Risk Buttons		N/C																
	Rural		N/C																
	Pause and Play Option		N/C																
[97]	N/C	-	N/C																
[106]	Tomorrow's Forecast	2	N/C																
	Prize		G																
[98]	Storytelling Sessions	3	O																
	Play with Joystick-based Console		N/C																
	Collaboration		M																
[99]	Integrating a Mini Game	1	N/C																
[100]	Main Character Explains to the Player and Dialogue	6	A/O																
	Different non-Player Characters		N/C																
	Different Game Features		N/C																
	Player's Objectives		C																
	Game tutorial		D																
[101]	Chatbot	2	N/C																
	List of Action Items		I																
[102]	Pick Different Emojis and Personalized Characters	4	K																
	Track the History of Monitored Information		L																
	Informational content		D																
	Chatbot to Answer Questions		H																
[103]	Suggests Proper Actions	2	N/C																
	Animated Narrative Cat		A																
[104]	Chatbot	2	H																
	List of Recommendation Actions		I																
[105]	Collaboration	8	M																
	Tutorial		D																
	Objectives		C																
	Content		N/C																
	Non-Playable Character (Guide/Hint)		A																
	Scores		E																
	Feedback		H																
	Users Can Choose the Role		I																
Frequency of occurrences of Game elements				4	2	5	4	5	1	1	2	6	4	1	5	3	1	2	2
Frequency of occurrences of Core Drives (CDs)				4	20							11			5	4		2	2



	2009	2014	2015	2016	2017	2020	2021	2022	2023
Others (2)	1					1			
Augmented Reality (4)			1			1	1		1
Laptops or PCs (4)				1		2	1		
Smartphones or Tablets (9)		1			2	2	2	2	

Fig. 8. Illustration of the types of delivery methods and applications.

Table 4
Categorization of game types, tool, and associated activities in the selected studies.

Tool/activity	2D Environment	3D Environment	AR Integration	Crowdsensing
Interactive Quizzes	✔			
Real-time Air Quality	✔	✔	✔	
Unity/Vuforia (AR)			✔	
Sensor Integration			✔	
Data Collection via Mobile (bicycle)				✔

Communication errors between the dose counter and the app related to rewards cause user frustration and mistrust. Relvas [100] reported occasional bugs, particularly in pause mode, displaying unpredictable behaviour such as unresponsiveness or needing closure. Although infrequent during testing, these issues could potentially lead to trainee frustration. Fernandes [105] documented that trainees accepted occasional tracking failures of markers (box and ring) as part of the game's challenges. Through trial and error, trainees developed strategies such as bringing the marker closer to the camera and maintaining parallel alignment with the image plane. The rest of the studies provided no information regarding the challenges they faced while using the application or the games.

4.8. Psychological and learning theories

This section also provides the results to answer the question eight of this study. Based on the findings, only a few psychological and learning theories or models have been employed to gamify air quality education. Niemeyer et al. [89] utilised John Dewey's theory, emphasising the integration of play and work in the curriculum. John Dewey's theory is known as progressive education, experiential learning, and problem-solving. This theory values the social aspect of learning, fosters democratic values, and views education as a lifelong, continuous process [112]. Grossman et al. [94] employed Captology and the Elaboration Likelihood Model (ELM) to enhance user engagement through a persuasion approach, offering a social influence framework. This theory suggests that there are two routes to persuasion: the central route, where people carefully consider information and arguments, and the peripheral route, where persuasion relies on factors such as the attractiveness or credibility of the source rather than the content of the message [113]. Also, Delmas and Kohli [106] focused on Theory of Planned Behaviour and the Theory of Issue Engagement, which show that having the intention to perform an action increases the likelihood of actually carrying out that action [114].

5. Discussion

The analysis of these selected papers was guided by the eight questions listed in Section 3.1. This study provides a further comprehensive understanding of the existing applications of gamification for air quality education. Based on the findings, the primary contexts explored in the eligible papers are IAQ, OAP, and both. In some cases, they just focused on the general environment. The main built environment/building typology is residential, which is the most common context. One study considered classrooms to assess the application of gamification. In addition, a study replicated Lisbon's Downtown as a virtual environment, and a study generally simulated a virtual environment to educate individuals about air pollution.

Regarding the learning objectives, the studies worked on educating the public about the impact of air pollution to enhance individuals' awareness of general pollutant exposure. These objectives extend further to educating the public about the health effects of air pollution and policies and fostering knowledge about air quality and healthy lifestyles. Additionally, the goals include improving children's understanding of asthma outcomes and promoting the routine habit of asthma control through education on the importance of air quality. The results of the eligible studies show that nine main game elements have been utilised for asthma management, including quest lists, points, win prizes, instant feedback, avatar, progress loss, choice perception, step-by-step tutorial, and progress bar (see Fig. 9).

Alternatively, Al-Rayes [115], who systematically reviewed the application of gamification in healthcare, highlighted that points, leaderboards, levels, feedback, and challenges are the predominant gaming elements utilised in gamified healthcare applications.

In this review, the most common game elements delivered by the application of gamification were also identified. In general, a total of sixteen game elements within the eligible articles were identified and associated with the reference game elements. As a result, forty-nine game elements (including the sum of all game elements mentioned in

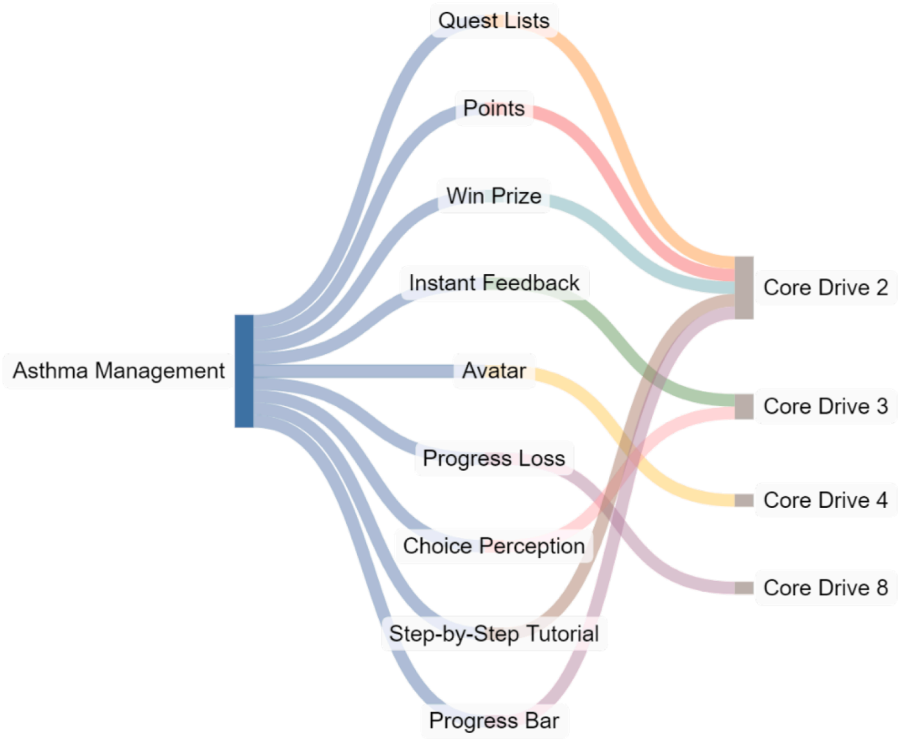


Fig. 9. Sankey diagram depicting the relationship between game elements and Core Drives (CDs) in the context of asthma management.

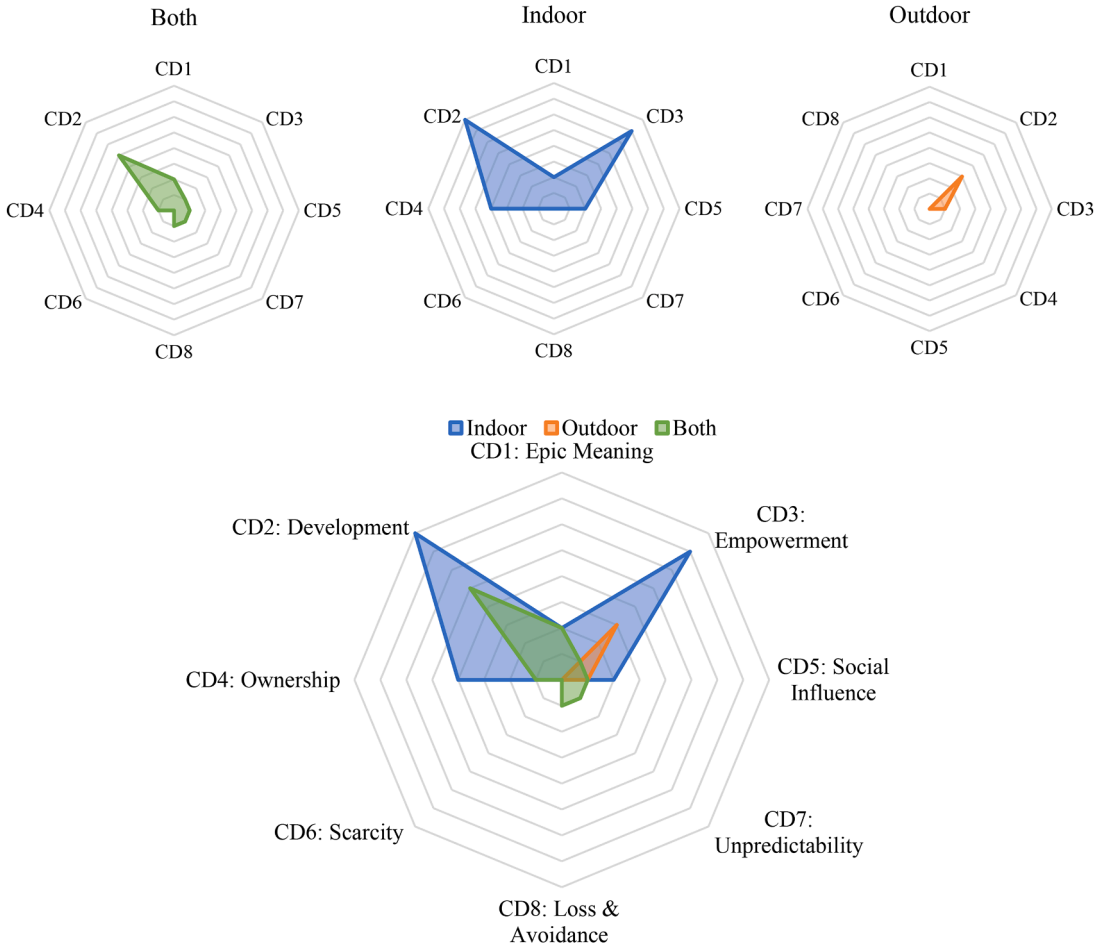


Fig. 10. The frequency of Core Drives and primary contexts through the process of the Octalysis framework. The scale ranges from 0 in the inner layer to 9 in the outer layer.

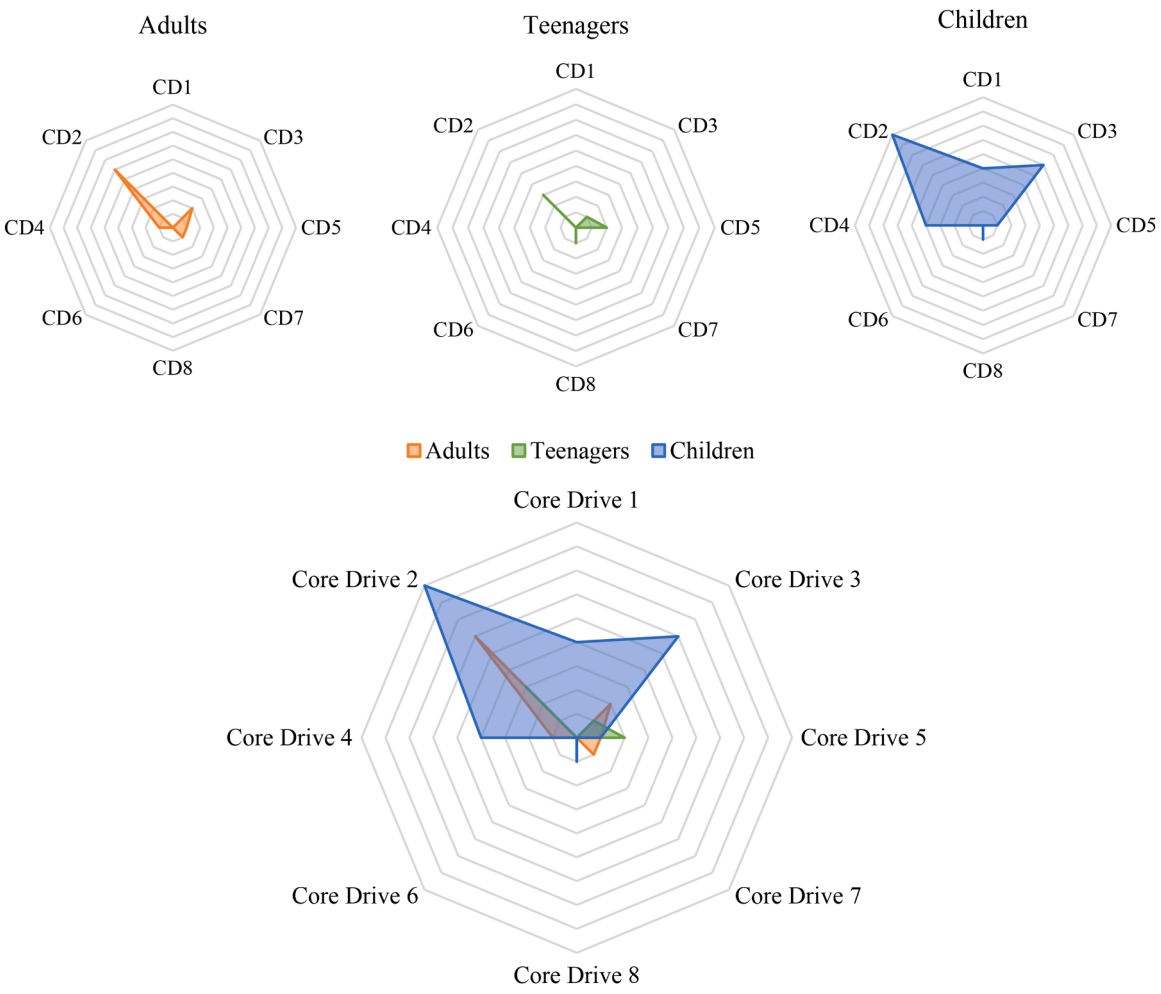


Fig. 11. The frequency of Core Drives and trainees through the process of the Octalysis framework. The scale ranges from 0 in the inner layer to 9 in the outer layer.

the same way in all the articles) have been linked to the reference game elements. CD2 (Development & Accomplishment) and CD3 (Empowerment of Creativity & Feedback) were the most used CDs by applying nineteen and eleven game elements, respectively. In CD2, 'Quest Lists' (5), 'Step-by-Step Tutorial' (4) and 'Points' (5), and in CD3, 'Instant Feedback' (6) were the most used game elements (see Table 3). Figs. 10 and 11 provide some information about the frequency of studies using CDs with primary contexts and trainees' profiles. These charts illustrate that each primary context and each group of trainees are linked with which CDs and highlight the overlap between the variables with CDs. More importantly, they show which CDs have been utilised more and which ones have not. Each parameter is presented in a separate chart due to insufficient or weak data for some parameters. Subsequently, these charts were consolidated into a single chart to enhance clarity.

The findings indicate that laptops or PCs were the primary delivery methods in four studies, while smartphones or tablets were used in 15 (see Fig. 8). These devices were often integrated with real-time data collection via sensors or crowdsensing through bicycles. Some studies reported positive feedback, improving trainees' awareness and engagement [89,90,95]. Others highlighted that their games were entertaining, fun, and easy to use [91,93]. Specifically, Carducci, et al. [92] found that 60 % of children learned something from the game, with a 1.40 % knowledge improvement post-assessment. Another study noted 60 % of trainees expressed willingness to use the application [99].

Users consistently reported positive engagement with environmental applications, with confirmed usability and feasibility sparking curiosity and generating positive feedback. Smartphone apps showed potential to enhance social responsibility and understanding of air pollution. Post-assessments revealed significant improvements in children's perceptions and increased parental involvement. However, trainees initially found the graphical interface helpful for identifying asthma triggers, but reduced app use due to perceived lack of interactivity [104]. Fernandes, et al. [105] showed a 50 % improvement in knowledge, with satisfaction and usability assessed through questionnaires.

Overall, the studies emphasize the effectiveness of the applications in raising air quality awareness, with high user engagement and positive feedback. The educational impact was evident in increased curiosity and improved knowledge. However, few studies directly compared delivery methods or applications. Fernandes et al. [105] found 85.2 % of trainees preferred using real objects, while 14.8 % preferred paper cards. Moreover, only a limited number of studies in air quality gamification have incorporated psychological theories [89,94,98,106], which are crucial for guiding intervention design and understanding behavioural change. While many reviews use meta-analysis to quantitatively assess research, this study faces limitations due to the lack of suitable quantitative data, restricting robust statistical analysis and the depth of insights.

5.1. *Proposed taxonomy for air quality-related serious games*

This work applied three approaches as foundations for proposing the taxonomy for air-quality related serious games/gamification, including the self-determination theory [116], the Octalysis framework [51], and the general taxonomy for serious games proposed by Breuer and Bente

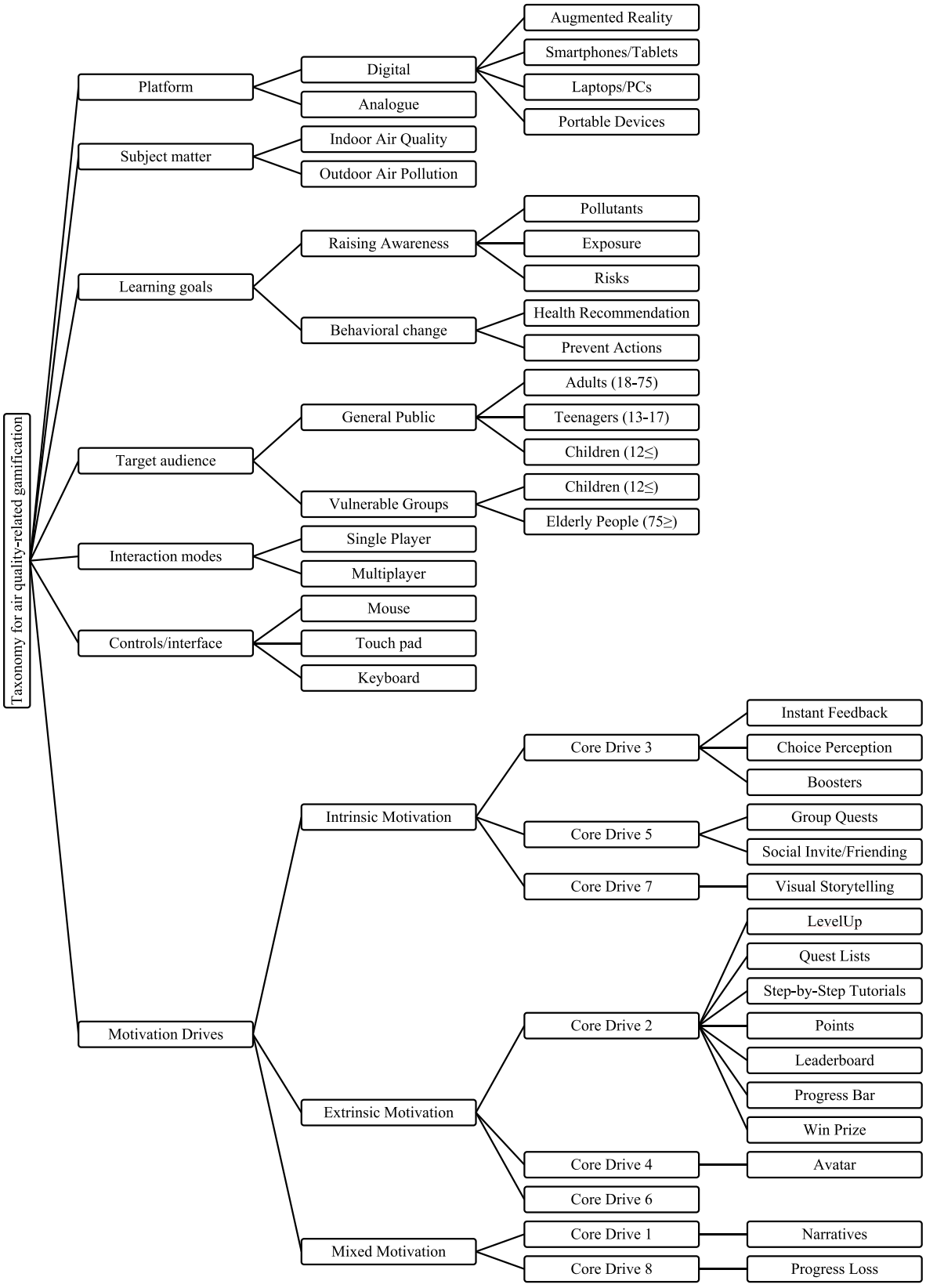


Fig. 12. Taxonomy and classification for air quality-related gamification.

[81]. To ensure a systematic and rigorous categorization of findings, the proposed taxonomy is grounded in these established theoretical frameworks. The self-determination theory provides insights into intrinsic and extrinsic motivation, which are essential to drive user engagement. In turn, the Octalysis framework offers a detailed breakdown of the Core Drives behind gamification, facilitating effective design strategies for behavioural change. Breuer and Bente's taxonomy was chosen because of its impact on the field. It provides a suitable starting point for a

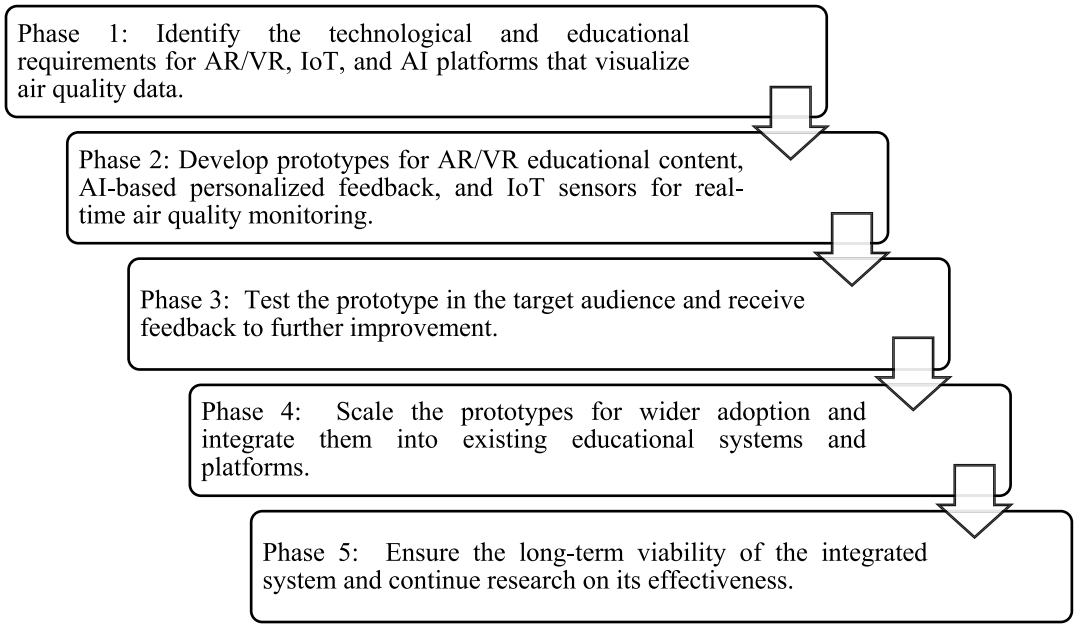


Fig. 13. Roadmap for implementing AR/VR, AI, and IoT in air quality education integrated with gamigication.

taxonomy within the field of air quality education. The proposed taxonomy is presented in Fig. 12.

While developing this taxonomy, the goal was to expand upon the original taxonomy proposed by Breuer and Bente [81] to include items related to air-quality gamification based on the findings of this review. The proposed taxonomy is divided into seven classifications: platform, subject matter, learning goals, target audience, interaction mode, controls/interface, and motivation drives. It should be noted that these classifications correspond to each research question addressed in this study. Also, each classification within the taxonomy is accompanied by illustrative examples, all of which are achieved as the results of this study. However, these examples should not constrain or limit future research to only these instances in the future use of this taxonomy to classify papers or to develop new gamification solutions. Ultimately, this taxonomy is intended to provide a foundational framework and inspire innovative approaches in the development of serious games and gamified applications within the air quality education field.

This study aligns with two Sustainable Development Goals, including #3 (Good Health and Well-being) and #11 (Sustainable Cities and Communities). By addressing respiratory issues (e.g., asthma) caused by air pollution, this research contributes to reducing hospitalizations and premature deaths from IAP. It is also addressed as this review explores the educational potential of gamification and serious games to deliver educational content to individuals in improving indoor environments. Ultimately, this work supports the creation of more sustainable and resilient cities.

The practical implications of this research span several domains. For academia, this research offers the foundation for future studies on gamification in air quality education. It introduces a taxonomy based on established theories, offering a systematic way to design, evaluate, and classify gamified applications. This taxonomy will guide researchers in creating innovative gamified solutions and foster further academic exploration in air quality education. We also identified key game elements, delivery methods, and learning objectives for educational applications. This research offers guidance for policymakers to integrate gamified strategies into public health and urban planning, promoting behavioural change and sustainable practices in communities. Also, the proposed roadmap (Fig. 13) offers guidelines to practical implementations of new technologies integrated with the applications.

5.2. *Research gaps and future directions*

This section provides the research gaps. First, the studies covered different types of built environments; however, other types of built environments, such as office buildings or public spaces (e.g., restaurants, libraries, etc.), have not been investigated (see Appendix A). One plausible explanation for this gap may stem from the complexity of controlling IAQ in specific scenarios, such as office buildings or libraries. Notably, the eligible studies focused solely on the health impact of air quality. For example, none of the studies specifically addressed knowledge retention in the context of air quality gamification. Effective knowledge retention in air quality gamification is paramount for ensuring a lasting impact on users, facilitating long-term behaviour change, and creating an informed decision-making [117]. Additionally, IAQ relates to the productivity and cognitive performance [118], sleep quality [119], human thermal comfort [120], and some aspects of environmental quality control, such as mould assessment [121].

In the following, evidence of behavioural impact was found in only one study [106], highlighting the necessity for further investigation into this crucial aspect. Many studies within the eligible studies did not conduct tests on their games with substantial sample sizes. Out of the examined papers, four studies assessed their games with fewer than ten trainees ($n \leq 10$), while nine studies extended their testing to up to thirty trainees ($n \leq 30$). Consequently, it can be inferred that most of these studies relied on relatively small sample sizes for testing their applications. Current literature indicates a limited adoption of AR integration in gamified approaches, with no studies utilising virtual reality headsets in game design. Furthermore, the majority of games are predominantly designed in 2D. Future research could explore innovative avenues by investigating the untapped potential of AR and VR technologies in gamification. Moreover, it is noteworthy that none of the studies incorporated simulations alongside the application of gamification. This limitation can be overcome in the future using various simulation-based scenarios that specifically address the importance of architectural strategies. i.e., windows and wind flow within buildings are used to control air pollution as well as mitigate energy consumption [6].

In addition, there is a lack of comparisons among different types of games, including traditional and innovative approaches (digital and non-digital) for the future direction. The effectiveness of these methods was not systematically assessed. Engaging a wider audience, especially

in regions where technology is not as advanced, presents a significant challenge for air quality education. In future research, it will be important to include both quantitative and qualitative analyses to assess how well these tools help users acquire and retain knowledge and whether they lead to lasting behaviour changes. A comparison of different types of games (traditional and digital) would also be valuable in understanding which methods work best for a better learning outcome. Engaging a wider audience, especially in regions where technology is not as advanced, presents a significant challenge for air quality education. Moreover, research connected to emerging technologies, such as AI and IoT-based environmental monitoring, is currently missing. Future studies should explore how these technologies can complement or enhance gamification tools. Fig. 13 illustrates a proposed research roadmap.

5.3. Application of learning theories

A few reviewed studies have incorporated learning theories within their applications to enhance learning outcomes. For instance, Niemeyer, et al. [89]] incorporated Dewey's theory about real-world experiences, role-play, and democratic learning structures. Dewey emphasized the idea of learning through experience [122]. In this study, students engaged with real-world air quality data collected via ``Pufftron'' air sensors to discuss real pollution issues with their peers. This practice exemplifies Dewey's vision of ``learning by doing'' and shows how gamification can align with experiential learning principles.

Grossman, et al. [94] applied Captology and the Elaboration Likelihood Model (ELM) to enhance game elements and learning outcomes. Captology focuses on using computers and digital tools to influence behaviour [123]. ELM explains how persuasion occurs through central (thoughtful) and peripheral (emotional or simple cues) routes [124]. In this study, Captology principles were used to design engaging feedback systems, like animations and cheering sounds, to reward positive behaviour instantly. Participants could customize avatars, promoting personal connection. The use of ELM was focused on peripheral persuasion, using simple visual cues, short motivational messages, and peer competition to encourage adherence. By combining interactive feedback with repetition, the proposed game aimed to build lasting habits and sustain positive behaviour change.

Delmas and Kohli [106] explored how mobile apps can boost user engagement with air quality information and encourage health-protective behaviours by applying the Theory of Planned Behaviour and the Theory of Issue Engagement. By stimulating users' intrinsic and extrinsic motivations, the app kept users engaged and improved their understanding of air pollution parameters. Users not only learned more about the health impacts of air pollution but also acted, adjusting their outdoor routines and using air filters to protect themselves.

6. Conclusion

This research systematically reviewed the application of gamification for air quality education by gathering data from nineteen papers published between 2009 and 2024. This work identified four delivery methods: augmented reality, smartphones/tablets, laptops/PCs, and portable devices. It also highlighted two main learning objectives: indoor air quality and outdoor air pollution. The Octalysis framework was used to classify the game elements used in the selected studies and their core drives. Sixteen distinct game elements were identified across the reviewed studies. "Accomplishement and Development" was the most frequently used core drive, linked with extrinsic motivation. The most common profiles of trainees are children and adults. All the studies employed digital games on smartphones, tablets, laptops, PCs, AR platforms, and portable devices. Future research should explore practical implementations of AR/VR, such as creating immersive experiences where users interact with real-world air pollution scenarios and view real-time air quality data to make informed decisions. Also, the identified educational theories include John Dewey's Experiential Learning, the Elaboration Likelihood Model for user engagement, the Theory of Planned Behaviour for intention and action correlation, and the Citizen Science approach for active user involvement in scientific research.

Data availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

CRediT authorship contribution statement

Abdollah Baghaei Daemei: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Conceptualization. **Ruggiero Lovreglio:** Writing – review & editing, Supervision, Conceptualization. **Zhenan Feng:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Daniel Paes:** Writing – review & editing, Supervision, Conceptualization. **Clayton Miller:** Writing – review & editing.

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.

Acknowledgements

The first author would like to thank Massey University for supporting his research through the Doctoral Scholarship program.

Appendix A. Summary of the eligible articles

Source	Q1	Q2	Q3		Q4	Q5	Q6	Q7	Q8
			Profile	N					
[89]	IAP (Classrooms)	Educating on the impact of air pollution on the environment and how they can positively change their environment	High school students	37	Various roles and teams, social interactions, different in-game activities,	A wireless cell phone-based real-time air quality monitoring device	Overall positive feedback	N/A	John Dewey Theory: Play and Work in the Curriculum
[90]	IAP and OAP	To raise users' understanding of their general	Adult (parents of children aged	80	Real-time feedback	A smartphone crowdsensing service	Curiosity was increased, leading to raising the	N/A	N/A

(continued on next page)

(*continued*)

Source	Q1	Q2	Q3		Q4	Q5	Q6	Q7	Q8
			Profile	N					
		exposure to pollutants	zero to ten years)			containing environmental data and a web application to visualise the data	citizen's motivation and awareness.		
[91]	IAP (General)	To teach users about air pollution and its effect on human health	Professional employees	23	Scores, choosing an avatar, points and awards, leaderboard	A non-immersive serious game application for smartphones, using real-time data monitoring	Positive feedback on simplicity for AR development, usability, available features and usage simplicity. It is reported that the game was entertaining	More tutorials are needed	N/A
[92]	IAP and OAP (Virtual environment)	To promote knowledge about air pollution and air quality, health effects, policies against pollution, and healthy lifestyles	Primary school children	266	Storyboard, choose a player (boy or girl), multiple levels, score and score reduction, objectives	Cartoon and videogames for PC	The video games were useful, understandable, simple, fun, and educational for children. Children reported enjoying the games, with 60 % stating that they learned something after playing. Additionally, pre- and post-assessments were conducted to measure changes in knowledge and perception. Post-assessment results showed a 1.40 % improvement in knowledge related to educational activities	N/A	N/A
[93]	Home IAQ monitoring (General)	To improve users' understanding of asthma clinical outcomes	Children aged seven to twelve years	4	Reminders, Feedback, Personalized character and avatar, Rewards and prizes, Task completion, answering questions, Secret code, Space locker, taking photos for postcards, Daily missions, Picking a name	A serious game involving a tablet application equipped with air quality monitors and spirometers	Users' engagement was improved; children rated the app as somewhat fun and helpful, but the exploration within the game was enjoyable	Non-portable air quality device has impacted the gameplay features	N/A
[94]	IAQ and asthma control (Home)	Encouraging the habit of daily asthma control to become a routine behaviour over time by educating them about the importance of air quality	Trainees aged eleven to sixteen years	12	Customisable avatar, scorecard, monetary award (to spend on GooglePlay), reminder, milestone or objective, dialogue box, rules, punishment, view their counterpart's score (like a competition), immediate feedback. Badge	A smartphone application integrating with a dose counter spirometer	N/A	Design limitation (positioning of the flashing light indicator and its visibility due to the plastic shell's opacity), lack of sturdiness of the dose counter, functional limitation occurring with rewards led to user frustration and mistrust due to unfulfilled app actions, communication errors between the dose counter	Captology and Elaboration Likelihood Model

(*continued on next page*)

(*continued*)

Source	Q1	Q2	Q3		Q4	Q5	Q6	Q7	Q8
			Profile	N					
								and the app and the study faced a logistical limitation related to trainees' access to electricity	
[95]	OAP (General)	To inform users about the importance of air quality and their exposure to air pollution	Adult	2	Motivations (fun and value), level and experience, achievements, registration and login, unlocking of achievements and position icons	A bicycle-based crowdsensing system, including real-time data collection with a web application for a smartphone	Positive users' engagement	N/A	N/A
[86]	OAP Visualizing (Virtual world)	To raise users' awareness of air pollution	Adults and young adults	30	Sitting on the bus as a passenger or by driving it, tasks, choosing different animated busses, tutorials, and help, two driving modes, text a non-text air pollution data visualisation, teleport option	A serious game designed for laptops (plus keyboard and mouse), in which animated buses can trace the movements of real buses using GPS technology and collect real-time data based on the actual city plans and buildings configuration	Usage success rate, satisfactory task completion times, positive user experience, increased user engagement, and overall positive results about objective and subjective analysis	It lacks a rich narrative and a poor interface design	N/A
[96]	IAP visualisation tool (General)	To increase users' awareness and understanding of air pollution as well as teach them about potential risks	Senior high school students	10	Filter options, information button, particles scale and risk buttons, rural, pause and play option	An immersive serious game for tablet or smartphone with real-time PM measurements	Usability and feasibility were confirmed, sparking curiosity and generating positive feedback	NA	N/A
[97]	OAP (General)	To increase social responsibility in environmental processes on air pollution	Undergraduate student	70	N/A	A smartphone environmental application connecting to online environmental information about air pollution	Using smartphone environmental application could increase trainees' social responsibility	N/A	N/A
[106]	IAP and OAP (General)	To educate on how to protect themselves against air pollution and promote changes in protective behaviour	Ranged from eighteen to sixty-five years	99	Tomorrow's forecast, prize,	A smartphone application integrating with the real-time data collection device	User experience was positive, and the application increased their understanding of air pollution	N/A	Theory of Planned Behaviour and the Theory of Issue Engagement
[98]	IAP and OAP (General)	To enhance users' understanding of air pollution	People ranged from eighteen to seventy-five years	25	Storytelling sessions, playing with the joystick-based console, collaboration,	Conventional technique: interactive web application air quality quizzes played with a computer or laptop with offline questionnaires and low-cost air quality monitoring sensors (+workshops)	The users' feedback regarding the tool was positive, awareness was raised, and the tools were engaging	N/A	NA

(*continued on next page*)

(*continued*)

Source	Q1	Q2	Q3		Q4	Q5	Q6	Q7	Q8
			Profile	N					
[99]	Monitoring IAQ	To promote users' knowledge about air pollution	Teenagers and youths	80	The editable main character, integrating a mini game	A serious game application for smartphones, including a sensor node for data collection	The feedback of willingness to use the application was positive by 60 % of the trainees.	NA	NA
[100]	IAP and OAP (Virtual world)	To raise perception about air pollution and learn the possible causes of air pollution	Elementary students	20	The main character explains to the player Different non-player characters, Different game features, the Player's objectives, Dialogue, Guidance,	A serious game application for a laptop or PC	The post-assessment showed the children's perception was significantly improved.	Some bugs were appearing while playing regarding the gameplay (the pause button did not work properly)	NA
[101]	IAP monitoring (Home)	To support users with asthma by monitoring and improving IAQ	Children aged eight to twelve years	12	Chatbot, List of action items (recommendations),	An application for smartphones	The children had little or no knowledge about IAP and how it affects their asthma.	NA	NA
[102]	IAP (Home)	To help users track their asthma condition and remind them about using a spirometer	Children aged eight to twelve years	12	Pick different emojis and personalised characters, track the history of the monitored information, provide Guidance, use Chatbot to answer questions,	Smartphone application with an IAQ sensor and a spirometer	NA	NA	NA
[103]	IAQ data visualisation (Home)	To raise understanding about IAQ	Children aged seven to ten years	9	Suggests proper actions, an animated narrative cat	An application for tablets which consists of real-time IAQ data	Positive initial interaction and feedback, as well as parents' involvement, was increased	NA	NA
[104]	IAQ data visualisation (Home)	To help users with asthma by improving IAQ	Children aged eight to twelve years	7	Chatbot, list of recommendation actions,	An application for smartphones interacting with real-time IAQ data	Initial impressions of the graphical interface were positive, and it was an effective tool for pediatric patients to check and confirm the source of an environmental asthma trigger. However, trainees reduced app use due to a lack of interactivity and fun.	NA	NA
[105]	IAP (Home, bedroom)	To improve users' knowledge about IAP	Elementary school children	27	Collaboration, Tutorial, Objectives, content, A non-playable character (to guide and hint), Scores and feedback, Users can choose the role,	A non-immersive serious game designed for laptops interacting with physical real-time sensor nodes	Results showed that knowledge was improved by about 50 %. Satisfaction and usability and questionnaire of opinion and preference were also assessed	Technical issue related to AR implementation (tracking the markers)	NA

IAP: Indoor Air Pollution.

Appendix B. Definition and usage of the retrieved game elements used within the eligible articles

Game elements (A to Q)	Definitions	Usage in the eligible papers	Sources
Narratives (A)	It offers players context about the games, providing a foundation to seamlessly introduce a compelling story [51].	*"An introductory video was shown to illustrate the main educational content of the games to the children."*	[92]
		"The scientist evaluates and explains to the player, via the main character, the possible causes regarding the air quality being displayed by each sensor placed in the several zones in the city" and *"A set of dialogue teaching participants about pollution."*	[100]
		"When we asked the participants to describe their experiences of using inAirKids during the early phase of the study, many dialogues were made from or reflected from the perspective of the animated cat on inAirKids."	[103]
		"To guide the experience and reinforce its didactic content, a non-playable character (NPC) was created. The NPC was a scientist, graphically represented with sprites, who appears only in key moments of the experience."	[105]
LevelUp (B)	This refers to a condition in which, once players level up, they can acquire a new set of skills while they are playing [51]. Levelling up is an application linked to player progress within a game in which players earn or unlock incentives associated with each level once they have acquired the necessary experience points [125].	*"The first game was developed at multiple levels. The first level was set in the city."*	[92]
		"Unlocking of achievements and position icons according to distance travelled and point of interests visited."	[95]
Quest Lists (C)	Refers to a specific task, mission, or objectives players undertake in a game [126].	*"The child earns rewards for completing tasks and answering questions required by the clinical protocol."* And *"Fig. 6 describes some sample interactions of daily missions involving the 3 planets and these activities."*	[93]
		"…the in-game objectives and scoring system will induce the need to explore the remaining objects further to discover how to use them and which ones produce gases."	[105]
		"…the "how to play" button, which shows a panel with text explaining what is happening in the city and the player's objectives."	[100]
		"The higher the intuitiveness of the tool, the better users can focus their cognitive effort on the primary task (e.g., planning the next vacations)…" and *"Participants had to complete each task without being helped and without time limit,…"*	[86]
		"Other messages are displayed as encouragement when certain milestones are missed."	[94]
Step-by-Step Tutorial (D)	The tutorial is a feature that aids the learning process, giving instructive content in video games to familiarise players with the gameplay [127, 128].	*"To help the user exploring all available features…a set of embedded tutorials inspired by in-game tutorials is available, as well as a help button."*	[86]
		"When beginning to play, participants also had a game tutorial to comprehend the controls and goals better when they started playing it."	[100]
		"…all apps offered informational content to encourage users to make beneficial, real-life changes."	[102]
		"…a small tutorial presented at the beginning of the gaming experience…"	[105]
Points (E)	Points refer to tokens that users can collect, which can be used as status indicators or to spend on virtual goods or gifting [129].	*"The collection of trees increase the user's score"* and *"The child with his avatar must collect the positive elements to increase the score…"*	[92]
		"The child earns rewards for completing tasks and answering questions required by the clinical protocol" and *"Space Locker: the child was able to accumulate prizes and postcards from visiting alien worlds and store them in the space locker."*	[93]
		"The closer the guess is, the more points are awarded."	[91]
		"The gamified experience comprises a scoring system, which rewards the user whenever gases or particles are directed to the window."	[105]
		"The scorecard at the bottom of the screen is updated as soon as the app receives a transmission…depending on the scoring rules…"	[94]
Leaderboard (F)	It is a game element where you rank users based on a set of criteria influenced by the users' behaviours towards the Desired Actions. Even though Leaderboards are meant to motivate people and bring in status, if misdesigned, they often do the exact opposite [51].	*"…a high score leader board visible to all players is generated."*	[91]
Progress Bar (G)	A progress bar is a visual game mechanic representing a player's advancement toward a specific goal or task completion [130].	*"…all apps provided the features to track the history or trend of the monitored information."*	[102]
Win Prize (H)	Win Prize refers to a gaming element where users or players can receive rewards or incentives upon achieving a specific goal, completing a challenge, or reaching a designated level of accomplishment within the game [51].	*"In the initial design, the participant was given a monetary award of $0.50, which was later changed to $1.00 to better motivate users. The amount was added to the scores on the trading card…"*	[94]
		"…a prize tab that incentivises people to respond to daily survey questions…"	[106]
Instant Feedback (I)	In gamification, feedback refers to the immediate and visible responses users receive from other users or experts, raising a sense of encouragement. This instant feedback mechanism intuitively enhances the user's perception of success and accomplishment [51].	*"The application is configured as an Android widget and provides real-time feedback with three layouts."*	[90]
		"This intends to be a simple way of providing feedback and assigning tasks to users, encouraging them to…"	[105]
		"Aspira allows families to continuously monitor indoor air quality on their own…" and "*We expect the real-time, objective feedback about indoor air quality to overcome knowledge barriers…"*	[93]
		"This immediate positive feedback of scoring a basket and receiving $0.50 to spend at the GooglePlay store motivated them to…"	[94]
		" a chatbot placed at the bottom left corner of the navigation bar. It answers questions regarding air quality and asthma in…"	[102]
		"a chatbot to ask any question relating to IAQ and asthma management…"	[104]

(continued on next page)

(*continued*)

Game elements (A to Q)	Definitions	Usage in the eligible papers	Sources
Choice Perception (J)	Choice Perception is the tendency for individuals to feel more intrinsically motivated when presented with multiple options or choices, emphasising the positive impact of perceived alternatives on motivation [131].	*"…we provided a list of action items that the user can perform to improve IAQ."*	[101]
		"Once they arrive at the game location, users choose the role they will play in the experience…"	[105]
		"The user can also choose to ride one of the animated city buses, allowing the user to effortlessly move across the city…"	[86]
		"…we provided a list of recommended actions that the user can take to improve the IAQ."	[104]
Boosters (K)	Boosters in a game, where players obtain something to help them achieve the win-state effectively [51].	*"…a "secret code" the child obtained to facilitate space travel."*	[93]
Avatar (L)	It is a graphical representation or character representing a user within the game or online platform. Avatars can be customised to reflect the user's preferences, allowing them to personalise their virtual identity [132].	*"The game is focused around avatar that the user selects at the start of the game. The avatar can be visualised through the AR view once the appropriate markers are detected."*	[91]
		"To increase the children's participation, they could choose either a boy or girl as a player."	[92]
		"The space-themed game involves a personalized character, or avatar,…"	[93]
		"…presenting an interactive and customizable avatar…"	[94]
		"…the apps for asthma management allowed users to pick different emojis and other colored graphical components…" and "…all apps used graphic characters and personified graphical components to make information more engaging and fun…"	[102]
Group Quest (M)	This feature is very effective in collaborative play as well as viral marketing because it requires group participation before any individual can achieve the Win-State [51].	*"…it is also a useful depiction of individual and group dynamics within the game."*	[89]
		"The main idea is to provide an environment where communities and scientists can collaborate towards a common goal that further leads to community capacity building."	[98]
		"The game was designed to be a cooperative multi-player, building upon the identified advantages of collaboration over competition in educational contexts."	[105]
Social Invite/ Friending (N)	This mechanism encourages players to connect with others, raising a sense of community, and often provides in-game benefits or collaborative opportunities tied to having a network of friends [133].	*"Participants were forced to research the lights, and, upon discovery, share the information through social interaction."*	[89]
Visual Storytelling (O)	Storytelling conveys events through words, sound, or images, serving various purposes. It includes oral traditions and techniques across different media to unfold narratives [134].	*"The storytelling sessions provided citizens a platform to*clearly present *their overall experience by contextualizing the story* i.e. *identifying the aim, …"*	[98]
		"…the scientist evaluates and explains to the player, via the main character, the possible causes regarding the air quality…"	[100]
Progress Loss (P)	It is a game element where players experience setbacks by losing their in-game progress or achievements. This element often serves as a consequence for failure or certain in-game events, adding challenge and strategic considerations to the gaming experience [51].	*"…the negative elements that reduce the score and block the game for 5 s."*	[92]
		"If the medicine is taken outside the prescribed time window, a message is displayed informing them that they missed their medication time and that they cannot receive a reward."	[94]

References

[1] Q. Liu, H. Li, W.-l. Shang, K. Wang, Spatio-temporal distribution of Chinese cities' air quality and the impact of high-speed rail, Renew. Sustain. Energy Rev. 170 (2022) 112970, https://doi.org/10.1016/j.rser.2022.112970.

[2] T.T. Moghadam, C.E. Ochoa Morales, M.J. Lopez Zambrano, K. Bruton, D.T. J. O'Sullivan, Energy efficient ventilation and indoor air quality in the context of COVID-19—A systematic review, Renew. Sustain. Energy Rev. 182 (2023) 113356, https://doi.org/10.1016/j.rser.2023.113356.

[3] X. Li, L. Jin, H. Kan, Air pollution: a global problem needs local fixes, Nature 570 (2019) 437–439, https://doi.org/10.1038/d41586-019-01960-7.

[4] J. Lelieveld, J.S. Evans, M. Fnais, D. Giannadaki, A. Pozzer, The contribution of outdoor air pollution sources to premature mortality on a global scale, Nature 525 (7569) (2015) 367–371, https://doi.org/10.1038/nature15371.

[5] R.A. Silva, et al., Future global mortality from changes in air pollution attributable to climate change, Nat. Clim. Change 7 (9) (2017) 647–651, https://doi.org/10.1038/nclimate3354.

[6] A. Buonomano, C. Forzano, G.F. Giuzio, A. Palombo, New ventilation design criteria for energy sustainability and indoor air quality in a post Covid-19 scenario, Renew. Sustain. Energy Rev. 182 (2023) 113378, https://doi.org/10.1016/j.rser.2023.113378.

[7] U. Satish, et al., Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance, Environ. Health Perspect. 120 (12) (2012) 1671–1677, https://doi.org/10.1289/ehp.1104789.

[8] S.S. Korsavi, A. Montazami, D. Mumovic, Perceived indoor air quality in naturally ventilated primary schools in the UK: impact of environmental variables and thermal sensation, Indoor Air 31 (2) (2021) 480–501.

[9] B. Unni, N. Tang, Y.M. Cheng, D. Gan, J. Aik, Community knowledge, attitude and behaviour towards indoor air quality: a national cross-sectional study in Singapore, Environ. Sci. Policy 136 (2022) 348–356. Available, https://www.sciencedirect.com/science/article/pii/S1462901122002064.

[10] WHO. "Health consequences of air pollution on populations." https://www.who.int/news/item/15-11-2019-what-are-health-consequences-of-air-pollution-on-populations#:~:text=It%20increases%20the%20risk%20of,poor%20people%20are%20more%20susceptible. (accessed 15 November, 2019.

[11] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, E. Bezirtzoglou, Environmental and health impacts of air pollution: a review, English, *Front. Public Health,* Rev. 8 (2020), https://doi.org/10.3389/fpubh.2020.00014.

[12] J.A. Bernstein, et al., The health effects of nonindustrial indoor air pollution, J. Allergy Clin. Immunol. 121 (3) (2008) 585–591, https://doi.org/10.1016/j.jaci.2007.10.045.

[13] B. Brunekreef, S.T. Holgate, Air pollution and health, Lancet 360 (9341) (2002) 1233–1242.

[14] M. Kampa, E. Castanas, Human health effects of air pollution, Environ. Pollut. 151 (2) (2008) 362–367.

[15] B. Zhang, et al., Comparison of particulate air pollution from different emission sources and incident dementia in the US, in eng, JAMA Intern. Med. 183 (10) (2023) 1080–1089, https://doi.org/10.1001/jamainternmed.2023.3300.

[16] M.N. Blanco, et al., Traffic-related air pollution and dementia incidence in the adult changes in thought study, Environ. Int. 183 (2024) 108418, https://doi.org/10.1016/j.envint.2024.108418.

[17] E. Underwood. "Brain pollution: evidence builds that dirty air causes Alzheimer's, dementia." Science. https://www.science.org/content/article/brain-pollution-evidence-builds-dirty-air-causes-alzheimer-s-dementia (accessed 29 January, 2024).

[18] J. Wang, et al., Ambient air pollution and the dynamic transitions of stroke and dementia: a population-based cohort study, EClinicalMedicine 67 (2024) 102368, https://doi.org/10.1016/j.eclinm.2023.102368.

[19] R. Aslam, F. Sharif, M. Baqar, A.-S. Nizami, U. Ashraf, Role of ambient air pollution in asthma spread among various population groups of Lahore City: a case study, Environ. Sci. Pollut. Res. 30 (4) (2023) 8682–8697, https://doi.org/10.1007/s11356-022-19086-1. Available.

[20] A. Steinemann, P. Wargocki, B. Rismanchi, Ten questions concerning green buildings and indoor air quality, Build. Environ. 112 (2017) 351–358, https://doi.org/10.1016/j.buildenv.2016.11.010.

[21] A. McCarron, S. Semple, C.F. Braban, V. Swanson, C. Gillespie, H.D. Price, Public engagement with air quality data: using health behaviour change theory to support exposure-minimising behaviours, J. Expo Sci. Environ. Epidemiol. 33 (3) (2023) 321–331, https://doi.org/10.1038/s41370-022-00449-2.

[22] J. Raufman, et al., Environmental health literacy and household air pollution-associated symptoms in Kenya: a cross-sectional study, in eng, Environ. Health 19 (1) (2020) 89, https://doi.org/10.1186/s12940-020-00643-5.

[23] M. Lindsey, S.R. Chen, R. Ben, M. Manoogian, J. Spradlin, Defining environmental health literacy, in eng, Int. J. Environ. Res. Public Health 18 (21) (2021), https://doi.org/10.3390/ijerph182111626.

[24] J.H. Kim, N. Moon, S.J. Heo, J.M. Kwak, Effects of environmental health literacy-based interventions on indoor air quality and urinary concentrations of polycyclic aromatic hydrocarbons, volatile organic compounds, and cotinine: a randomized controlled trial, Atmos. Pollut. Res. 15 (1) (2024) 101965, https://doi.org/10.1016/j.apr.2023.101965.

[25] B.D. Douglas, M. Brauer, Gamification to prevent climate change: a review of games and apps for sustainability, in English, *Curr. Opin. Psychol.,* Rev. 42 (2021) 89–94. Available, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85106628168&doi=10.1016%2fj.copsyc.2021.04.008&partnerID=40&md5=81f5c754ea9bbc1a3c3e0c98b35b8f75.

[26] D. Johnson, S. Deterding, K.-A. Kuhn, A. Staneva, S. Stoyanov, L. Hides, Gamification for health and wellbeing: a systematic review of the literature, Internet Interv. 6 (2016) 89–106, https://doi.org/10.1016/j.invent.2016.10.002.

[27] B. Long, J. Simson, D.G. Watson, S.A. Mehr, How games can make behavioural science better, Nature (2023). Available, https://www.nature.com/articles/d41586-023-00065-6.

[28] S. Kim, K. Song, B. Lockee, J. Burton, What is gamification in learning and education?. Gamification in Learning and Education: Enjoy Learning Like Gaming Springer International Publishing, Cham, 2018, pp. 25–38.

[29] S. De Jans, K. Van Geit, V. Cauberghe, L. Hudders, M. De Veirman, Using games to raise awareness: how to co-design serious mini-games? Comput. Educ. 110 (2017) 77–87 [Online]. Available, https://www.sciencedirect.com/science/article/pii/S0360131517300581.

[30] À. Boso, B. Álvarez, C. Oltra, J. Garrido, C. Muñoz, Á. Hofflinger, Out of sight, out of mind: participatory sensing for monitoring indoor air quality, Environ. Monit. Assess. 192 (2) (2020) 104, https://doi.org/10.1007/s10661-019-8058-z.

[31] A. Behl, N. Jayawardena, S. Bhardwaj, V. Pereira, M. del Giudice, J. Zhang, Examining the failure of gamification in implementing innovation from the perspective of problematization in the retail sectors of emerging economies, Technovation 129 (2024) 102902, https://doi.org/10.1016/j.technovation.2023.102902.

[32] P. Buckley, E. Doyle, Gamification and student motivation, Interact. Learn. Environ. 24 (6) (2016) 1162–1175, https://doi.org/10.1080/10494820.2014.964263.

[33] B. Kim, Harnessing the power of game dynamics: why, how to, and how not to gamify the library experience, Coll. Res. Lib. News 73 (2012) 465–469, https://doi.org/10.5860/crln.73.8.8811.

[34] R. van Roy, B. Zaman, Need-supporting gamification in education: an assessment of motivational effects over time, Comput. Educ. 127 (2018) 283–297, https://doi.org/10.1016/j.compedu.2018.08.018.

[35] B. Barna and S. Fodor, "An Empirical Study on the Use of Gamification on IT Courses at Higher Education," 2018, pp. 684–692.

[36] I. Yildirim, The effects of gamification-based teaching practices on student achievement and students' attitudes toward lessons, Internet High. Educ. 33 (2017) 86–92, https://doi.org/10.1016/j.iheduc.2017.02.002.

[37] Z. Feng, V.A. González, C. Mutch, R. Amor, G. Cabrera-Guerrero, Instructional mechanisms in immersive virtual reality serious games: earthquake emergency training for children, J. Comput. Assist. Learn. 37 (2) (2021) 542–556, https://doi.org/10.1111/jcal.12507.

[38] M. Çoban, Y. Göktaş, Comparison of the digital game, drills, and traditional education methods in terms of motivation in earthquake education, E-Learn. Digit. Media 20 (1) (2023) 25–52.

[39] S.F. Mirsoleymani, K.F. Vajargah, K. Pushaneh, A.A. Khosravi, M. Vahidi-Asl, The effect of earthquake preparedness training courses through gamification on the students' knowledge level, J. Posit. Sch. Psychol. 6 (5) (2022) 9945–9954.

[40] R. Lovreglio, X. Duan, A. Rahouti, R. Phipps, D. Nilsson, Comparing the effectiveness of fire extinguisher virtual reality and video training, Virtual Real. 25 (1) (2021) 133–145, https://doi.org/10.1007/s10055-020-00447-5.

[41] G. Kazar, S. Comu, Effectiveness of serious games for safety training: a mixed method study, J. Constr. Eng. Manag. 147 (8) (2021) 04021091, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002119.

[42] S. Lu, Z. Feng, R. Lovreglio, F. Wang, and X. Yuan, "Comparing the productive failure and directive instruction for declarative safety knowledge training using virtual reality," *J. Comput. Assist. Learn.*, vol. n/a, no. n/a, doi: https://doi.org/10.1111/jcal.12937.

[43] L.C. Tagliabue, S.M. Ventura, J. Teizer, A.L. Ciribini, A serious game for lean construction education enabled by internet of things, in: Ludic, Co-design and Tools Supporting Smart Learning Ecosystems and Smart Education: Proceedings of the 5th International Conference on Smart Learning Ecosystems and Regional Development, Springer, 2020, pp. 225–233.

[44] N.I. Mohd, K.N. Ali, S. Bandi, F. Ismail, Exploring gamification approach in hazard identification training for Malaysian construction industry, Int. J. Built Environ. Sustain. 6 (1) (2019) 51–57.

[45] K.K. Ren, N.I. Mohd, K.N. Ali, S. Bandi, F. Ismail, Design phase of gamification framework for hazard identification training in construction industry, Int. J. Interact. Mob. Technol. 16 (2) (2022).

[46] J. Cavalcanti, V. Valls, M. Contero, D. Fonseca, Gamification and hazard communication in virtual reality: a qualitative study, Sensors 21 (14) (2021) 4663.

[47] F. Taillandier, C. Adam, Games ready to use: a serious game for teaching natural risk management, Simul. Gaming 49 (4) (2018) 441–470.

[48] A.K.H. Lai, et al., A comparison between the effectiveness of a gamified approach with the conventional approach in point-of-care ultrasonographic training, BMC Med. Educ. 20 (1) (2020) 263, https://doi.org/10.1186/s12909-020-02173-7.

[49] M. Ilbeigi, D. Bairaktarova, R. Ehsani, A gamified method for construction engineering education: learning through guided active exploration, J. Civ. Eng. Educ. 150 (2) (2024) 05023011, https://doi.org/10.1061/JCEECD.EIENG-2019.

[50] S. Villagrasa, D. Fonseca, J. Durán, Teaching case: applying gamification techniques and virtual reality for learning building engineering 3D arts, in: Presented at the Proceedings of the Second International Conference on Technological Ecosystems for Enhancing Multiculturality, Salamanca, Spain, 2014, https://doi.org/10.1145/2669711.2669896. Available.

[51] Y.-k. Chou, Actionable Gamification: Beyond Points, Badges, and Leaderboards, 2019th edition, Octalysis Media, 2015.

[52] W. Oliveira, et al., Tailored gamification in education: a literature review and future agenda, Educ. Inf. Technol. 28 (1) (2023) 373–406, https://doi.org/10.1007/s10639-022-11122-4.

[53] G. Zichermann, C. Cunningham, Gamification by Design: Implementing Game Mechanics in Web and Mobile Apps, O'Reilly Media, Inc., 2011.

[54] R.S. Alsawaier, The effect of gamification on motivation and engagement, Int. J. Inf. Learn. Technol. 35 (1) (2018) 56–79, https://doi.org/10.1108/IJILT-02-2017-0009.

[55] W. Sharma, W.M. Lim, S. Kumar, A. Verma, R. Kumra, Game on! A state-of-the-art overview of doing business with gamification, Technol. Forecast. Soc. Change 198 (2024) 122988, https://doi.org/10.1016/j.techfore.2023.122988.

[56] E.D. Mekler, F. Brühlmann, A.N. Tuch, K. Opwis, Towards understanding the effects of individual gamification elements on intrinsic motivation and performance, Comput. Hum. Behav. 71 (2017) 525–534, https://doi.org/10.1016/j.chb.2015.08.048.

[57] T. Susi, M. Johannesson, and P. Backlund, "Serious games: an overview," 2007.

[58] C.C. Abt, Serious Games, University Press of America, 1987.

[59] U. Ritterfeld, M. Cody, P. Vorderer, Serious Games: Mechanisms and Effects, Routledge, 2009.

[60] D. Yates, 3. Why so serious? The role of non-serious games in sparking educational curiosity: a reflection. Games, Simulations and Playful Learning in Business Education, 2021, p. 23.

[61] R. McDaniel, S.M. Fiore, D. Nicholson, Serious storytelling: narrative considerations for serious games researchers and developers. Serious Game Design and Development: Technologies for Training and Learning, IGI Global, 2010, pp. 13–30.

[62] N. Naik, A comparative evaluation of game-based learning: digital or non-digital games?, in: European Conference on Games Based Learning 2 Academic Conferences International Limited, 2014, p. 437.

[63] S. Naderi, F. Moafian, The victory of a non-digital game over a digital one in vocabulary learning, Comput. Educ. Open 4 (2023) 100135, https://doi.org/10.1016/j.caeo.2023.100135.

[64] C. Jennett, et al., Measuring and defining the experience of immersion in games, Int. J. Hum. Comput. Stud. 66 (9) (2008) 641–661, https://doi.org/10.1016/j.ijhcs.2008.04.004.

[65] E. Brown, P. Cairns, A grounded investigation of game immersion, in: Presented at the CHI '04 Extended Abstracts on Human Factors in Computing Systems, Vienna, Austria, 2004, https://doi.org/10.1145/985921.986048. Available.

[66] J. Porter III, M. Boyer, A. Robb, Guidelines on successfully porting non-immersive games to virtual reality: a case study in Minecraft, in: Presented at the Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play, Melbourne, VIC, Australia, 2018, https://doi.org/10.1145/3242671.3242677. Available.

[67] F. Pallavicini, A. Pepe, M.E. Minissi, Gaming in virtual reality: what changes in terms of usability, emotional response and sense of presence compared to non-immersive video games? Simul. Gaming 50 (2) (2019) 136–159, https://doi.org/10.1177/1046878119831420.

[68] A.C. Lewis, D. Jenkins, C.J.M. Whitty, Hidden harms of indoor air pollution—Five steps to expose them, Nature (614) (2023) 220–223, https://doi.org/10.1038/d41586-023-00287-8.

[69] P. Picciano, M. Qiu, S.D. Eastham, M. Yuan, J. Reilly, N.E. Selin, Air quality related equity implications of U.S. decarbonization policy, Nat. Commun. 14 (1) (2023) 5543, https://doi.org/10.1038/s41467-023-41131-x.

[70] H. Akimoto, Global air quality and pollution, Science 302 (5651) (2003) 1716–1719, https://doi.org/10.1126/science.1092666.

[71] D.E. Marcotte, Something in the air? Air quality and children's educational outcomes, Econ. Educ. Rev. 56 (2017) 141–151, https://doi.org/10.1016/j.econedurev.2016.12.003.

[72] I.L. Auerbach, K. Flieger, The importance of public education in air pollution control, in eng, J. Air Pollut. Control Assoc. 17 (2) (1967) 102–104, https://doi.org/10.1080/00022470.1967.10468947.

[73] A. Barbosa, et al., GReSBAS project: a gamified approach to promote more energy efficient behaviours in buildings, in: 2017 10th International Conference on Electrical and Electronics Engineering (ELECO), 30 Nov.–2 Dec. 2017, 2017, pp. 1258–1261.

[74] F.J. Kelly, J.C. Fussell, Air pollution and public health: emerging hazards and improved understanding of risk, Environ. Geochem. Health 37 (4) (2015) 631–649, https://doi.org/10.1007/s10653-015-9720-1.

[75] T. Arcury, Environmental attitude and environmental knowledge, Hum. Organ. 49 (4) (1990) 300–304.

[76] Y. Wang, M. Sun, X. Yang, X. Yuan, Public awareness and willingness to pay for tackling smog pollution in China: a case study, J. Clean. Prod. 112 (2016) 1627–1634, https://doi.org/10.1016/j.jclepro.2015.04.135.

[77] A. Moreira, F. de Castro Mendes, T. Rama, D. Mota, D. Silva, et al., AlergiaPT: a Portuguese media campaign to inspire people with allergies to make a positive change in their life, Porto Biomed. J. 7 (1) (2022) e169. Available, https://ezproxy.massey.ac.nz/login?url=https://search.ebscohost.com/login.aspx?direct=true&AuthType=sso&db=edsovi&AN=edsovi.02054639.202204000.00003&site=eds-live&scope=site&authtype=sso&custid=s3027306.

[78] E. Polychronidou, A. Lalas, D. Tzovaras, and K. Votis, "A systematic distributing sensor system prototype for respiratory diseases," ed: IEEE, 2019, pp. 191–196.

[79] D. Tranfield, D. Denyer, P. Smart, Towards a methodology for developing evidence-informed management knowledge by means of systematic review, Br. J. Manag. 14 (3) (2003) 207–222, https://doi.org/10.1111/1467-8551.00375.

[80] K.S. Khan, R. Kunz, J. Kleijnen, G. Antes, Five steps to conducting a systematic review, J. R. Soc. Med. 96 (3) (2003) 118–121, https://doi.org/10.1177/014107680309600304.

[81] J. Breuer, G. Bente, Why so serious? On the relation of serious games and learning, J. Comput. Game Cult. 4 (2010) 7–24.

[82] D. Scorgie, Z. Feng, D. Paes, F. Parisi, T.W. Yiu, R. Lovreglio, Virtual reality for safety training: a systematic literature review and meta-analysis, Saf. Sci. 171 (2024) 106372, https://doi.org/10.1016/j.ssci.2023.106372.

[83] Elsevier. Available from: https://www.elsevier.com/solutions/scopus/why-choose-scopus#:~:text=Scopus%20helps%3A,bolster%20performance%2C%20rank%2C%20and%20reputation (accessed.

[84] A. Martín-Martín, M. Thelwall, E. Orduna-Malea, E. Delgado López-Cózar, Google scholar, microsoft academic, Scopus, dimensions, web of science, and OpenCitations' COCI: a multidisciplinary comparison of coverage via citations, Scientometrics. 126 (1) (2021) 871–906, https://doi.org/10.1007/s11192-020-03690-4.

[85] IEEE. "IEEE at a Glance." Avalilable from: https://www.ieee.org/about/at-a-glance.html (accessed Last updated December 2022).

[86] B. Teles, P. Mariano, P. Santana, Game-like 3D visualisation of air quality data, Multimodal Technol. Interact. 4 (54) (2020) 54, https://doi.org/10.3390/mti4030054.

[87] C. Wohlin, Guidelines for snowballing in systematic literature studies and a replication in software engineering, in: Presented at the Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering, London, England, United Kingdom, 2014, https://doi.org/10.1145/2601248.2601268. Available.

[88] C. Wohlin, M. Kalinowski, K.R. Felizardo, E. Mendes, Successful combination of database search and snowballing for identification of primary studies in systematic literature studies, Inf. Softw. Technol. 147 (2022) 106908, https://doi.org/10.1016/j.infsof.2022.106908.

[89] G. Niemeyer, A. Garcia, R. Naima, Black cloud: patterns towards da future, in: MM'09 - Proceedings of the 2009 ACM Multimedia Conference, with Co-located Workshops and Symposiums, 2009, pp. 1073–1082, https://doi.org/10.1145/1631272.1631514. Available, https://www.scopus.com/inward/record.uri?eid=2-s2.0-72449175203&doi=10.1145%2f1631272.1631514&partnerID=40&md5=1d4da68a268242307ff56e849375f2d4.

[90] C. Leonardi, A. Cappellotto, M. Caraviello, B. Lepri, F. Antonelli, SecondNose: an air quality mobile crowdsensing system, in: Presented at the Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational, Helsinki, Finland, 2014. Available: doi.org.ezproxy.massey.ac.nz/10.1145/2639189.2670273.

[91] B. Pokric, et al., Augmented reality enabled IoT services for environmental monitoring utilising serious gaming concept (in English), J. Wirel. Mob. Netw. Ubiquitous. Comput. Dependable Appl. 6 (1) (2015) 37–55. Available, https://www.scopus.com/inward/record.uri?eid=2-s2.0-84926287740&partnerID=40&md5=e77ddc05749017ccbc9dd014d89ae55c.

[92] A. Carducci, et al., Improving awareness of health hazards associated with air pollution in primary school children: design and test of didactic tools, in English, Appl. Environ. Educ. Commun 15 (3) (2016) 247–260, https://doi.org/10.1080/1533015X.2016.1181017.

[93] J. Thomson, et al., Aspira: employing a serious game in an mHealth app to improve asthma outcomes, in: 2017 IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH), 2017, pp. 1–7, https://doi.org/10.1109/SeGAH.2017.7939268.

[94] B. Grossman, et al., Application of human augmentics: a persuasive asthma inhaler, J. Biomed. Inform. 67 (2017) 51–58, https://doi.org/10.1016/j.jbi.2017.02.003.

[95] M. Bosello, G. Delnevo, S. Mirri, On exploiting gamification for the crowdsensing of air pollution: a case study on a bicycle-based system, in: ACM International Conference Proceeding Series, Association for Computing Machinery, 2020, pp. 205–210, https://doi.org/10.1145/3411170.3411256. Available, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85091283957&doi=10.1145%2f3411170.3411256&partnerID=40&md5=1017d05d3cf8fd122507f4a1157bd5cc.

[96] F.E. Campana, F.X. Dominguez, Proposal of a particulate matter measurement device and an augmented reality visualization app as an educational tool, in: 2020: Proceedings of the 12th International Conference on Education Technology and Computers, 2020, pp. 6–11.

[97] A. Varnavsky, Research of urban residents involvement in environmental processes using a mobile environmental application, in: Presented at the International Conference on Convergent Cognitive Information Technologies, Moscow, Russia, 2020.

[98] S. Mahajan, et al., A citizen science approach for enhancing public understanding of air pollution, Sustain. Cities Soc. 52 (2020) 101800, https://doi.org/10.1016/j.scs.2019.101800.

[99] T.Y. Ling, Y.B. Teh, G.K. Kiat Ting, W.Z. Wong, N.H. Mahmood, Project kappa: an augmented-reality based sensor data crowdsourcing platform for environmental monitoring, in: *2021 IEEE International Conference on Sensors and Nanotechnology, SENNANO* 2021, Institute of Electrical and Electronics Engineers Inc., 2021, pp. 17–20, https://doi.org/10.1109/SENNANO51750.2021.9642575. Available, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85124035109&doi=10.1109%2fSENNANO51750.2021.9642575&partnerID=40&md5=783bdddf7236c5caa0636fb2ca24d684.

[100] T.M.B. Relvas, A Serious Game for Raising Air Pollution Awareness in Children, ProQuest Dissertations Publishing, 2021.

[101] S.K. Shabanabegum, P.V.S. Varun, R. Sai Mohan Krishna, S.M. Rasool, Air quality measurment app for children with asthma, Turkish Online J. Qual. Inq. 12 (9) (2021) 7111–7119. Available, https://ezproxy.massey.ac.nz/login?url=https://search.ebscohost.com/login.aspx?direct=true&AuthType=sso&db=eue&AN=160605033&site=eds-live&scope=site&authtype=sso&custid=s3027306.

[102] S. Kim, Y. Park, M.K. Ackerman, Designing an indoor air quality monitoring app for asthma management in children: user-centered design approach, in English, JMIR Form. Res. 5 (9) (2021) e27447, https://doi.org/10.2196/27447.

[103] S. Kim, G. Sohanchyk, Exploring children's engagement in monitoring indoor air quality: longitudinal study, in English, JMIR Form. Res. 6 (1) (2022), https://doi.org/10.2196/32404.

[104] S. Kim, K. Stanton, Y. Park, S. Thomas, A mobile app for children with asthma to monitor indoor air quality (AirBuddy): development and usability study, in English, JMIR Form. Res. 6 (5) (2022) e37118, https://doi.org/10.2196/37118.

[105] J. Fernandes, T. Brandão, S.M. Almeida, P. Santana, An educational game to teach children about air quality using augmented reality and tangible interaction with sensors, in English, Int. J. Environ. Res. Public Health 20 (5) (2023) 3814, https://doi.org/10.3390/ijerph20053814.

[106] M.A. Delmas, A. Kohli, Can apps make air pollution visible? Learning about health impacts through engagement with air quality information, J. Bus. Ethics 161 (2) (2020) 279–302, https://doi.org/10.1007/s10551-019-04215-7.

[107] S. Rabin, *Introduction to Game Development* Charles River Media, 2009.

[108] C.-M. Chen, L. Ming-Chaun, C.-P. Kuo, A game-based learning system based on octalysis gamification framework to promote employees' Japanese learning, Comput. Educ. 205 (2023) 104899, https://doi.org/10.1016/j.compedu.2023.104899.

[109] J. Karać, M. Stabauer, Gamification in E-commerce. HCI in Business, Government and Organizations. Supporting Business, Springer International Publishing, Cham, 2017, pp. 41–54.

[110] S. Aviv-Reuven, A. Rosenfeld, Publication patterns' changes due to the COVID-19 pandemic: a longitudinal and short-term scientometric analysis, in eng, Scientometrics. 126 (8) (2021) 6761–6784, https://doi.org/10.1007/s11192-021-04059-x.

[111] M. Raynaud, et al., Impact of the COVID-19 pandemic on publication dynamics and non-COVID-19 research production, BMC Med. Res. Methodol. 21 (1) (2021) 255, https://doi.org/10.1186/s12874-021-01404-9.

[112] D. Gajic, Roberto Gronda: Dewey's philosophy of science, J. Gen. Philos. Sci. (2024), https://doi.org/10.1007/s10838-023-09665-2.

[113] R.E. Petty and J.T. Cacioppo, in *Advances in Experimental Social Psychology*, vol. 19, L. Berkowitz (Ed.): Academic Press, 1986, pp. 123–205.

[114] I. Ajzen, The theory of planned behavior, Organ. Behav. Hum. Decis. Process. 50 (2) (1991) 179–211, https://doi.org/10.1016/0749-5978(91)90020-T.

[115] S. Al-Rayes, et al., Gaming elements, applications, and challenges of gamification in healthcare, Inform. Med. Unlocked 31 (2022) 100974, https://doi.org/10.1016/j.imu.2022.100974.

[116] M. Gagné, E.L. Deci, Self-determination theory and work motivation, J. Organ. Behav. 26 (4) (2005) 331–362.

[117] K. Madani, T.W. Pierce, A. Mirchi, Serious games on environmental management, Sustain. Cities Soc. 29 (2017) 1–11, https://doi.org/10.1016/j.scs.2016.11.007.

[118] X. Zhang, J. Du, D. Chow, Association between perceived indoor environmental characteristics and occupants' mental well-being, cognitive performance, productivity, satisfaction in workplaces: a systematic review, Build. Environ. 246 (2023) 110985, https://doi.org/10.1016/j.buildenv.2023.110985.

[119] P. Strøm-Tejsen, D. Zukowska, P. Wargocki, D.P. Wyon, The effects of bedroom air quality on sleep and next-day performance, Indoor Air 26 (5) (2016) 679–686, https://doi.org/10.1111/ina.12254.

[120] N. Ma, D. Aviv, H. Guo, W.W. Braham, Measuring the right factors: a review of variables and models for thermal comfort and indoor air quality, Renew. Sustain. Energy Rev. 135 (2021) 110436, https://doi.org/10.1016/j.rser.2020.110436.

[121] J. Qiao, X. Zhang, F. Xiao, Y. Li, W. Gao, Experimental investigation of mold growth risk among typical residential indoor materials: case study in coastal city, China, Energy Build. 304 (2024) 113885, https://doi.org/10.1016/j.enbuild.2024.113885.

[122] J. Dewey, Democracy and Education: An Introduction to the Philosophy of Education, The Pennsylvania State University, 2001.

[123] B.J. Fogg, G. Cueller, D. Danielson, Motivating, influencing, and persuading users: an introduction to captology. The Human-Computer Interaction Handbook, CRC Press, 2007, pp. 159–172.
[124] R.E. Petty, P. Briñol, The elaboration likelihood model, Handb. Theor. Soc. Psychol. 1 (2011) 224–245.
[125] J. McFarland, Leveling up for the teacher-practitioner: design and implementation of a gamified application, Schools 17 (1) (2020) 115–135.
[126] R. Naraghi-Taghi-Off, R. Horst, and R. Dörner, *Gamification Mechanics for Playful Virtual Reality Authoring*. 2020.
[127] E. Andersen, et al., The impact of tutorials on games of varying complexity, in: Presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Austin, Texas, USA, 2012, https://doi.org/10.1145/2207676.2207687. Available.
[128] S. Cao, F. Liu, Learning to play: understanding in-game tutorials with a pilot study on implicit tutorials, in eng, Heliyon 8 (11) (2022) e11482, https://doi.org/10.1016/j.heliyon.2022.e11482.
[129] B. Huang and K. Hew, *Do points, badges and leaderboard increase learning and activity: a quasi-experiment on the effects of gamification*. 2015.
[130] M. Kosyakoff. "Fill the progress. How to design the perfect game progress bar?" https://medium.com/@MaxKosyakoff/fill-the-progress-fc0fa99cabac (accessed 3rd of June, 2024).
[131] S.S. Iyengar, M.R. Lepper, When choice is demotivating: can one desire too much of a good thing?, in eng, J. Pers. Soc. Psychol. 79 (6) (2000) 995–1006, https://doi.org/10.1037//0022-3514.79.6.995.
[132] K. Szolin, D.J. Kuss, F.M. Nuyens, M.D. Griffiths, I am the character, the character is me": a thematic analysis of the user-avatar relationship in videogames, Comput. Hum. Behav. 143 (2023) 107694, https://doi.org/10.1016/j.chb.2023.107694.
[133] M. Consalvo, Using your friends: social mechanics in social games, in: Proceedings of the 6th International Conference on Foundations of Digital Games, 2011, pp. 188–195.
[134] M. Giakalaras, "Gamification and Storytelling," 2016.