

# Developing a serious game for indoor air quality and mold prevention education in residential buildings

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## Abstract

**Purpose** – This study explores the development and prototyping of a serious game aimed at teaching individuals how to prevent mold growth in homes.

**Design/methodology/approach** – The development process involved several steps including identifying learning objectives based on Bloom's Taxonomy, establishing educational content through literature review, designing game mechanics followed by Octalysis, designing the game's narrative and storyline, developing the prototype using Storyline 360, verifying the educational content via interview and home visit, and refining it through the verification outcomes.

**Findings** – Key findings highlighted the most mold-prone areas in the kitchen, bedroom, and bathroom, the main factors contributing to mold growth: moisture, cold surfaces, nutrients, and spores. Also, the study recommends maintaining indoor temperatures between 20–24°C and humidity levels between 40–60% to prevent mold and keep moisture levels in check. Practical mold prevention strategies were identified and integrated into the game. The game incorporates a variety of mechanics, including narrative, points, progress bars, quest lists, step-by-step tutorials, level-ups, milestone unlocks, instant feedback, avatars, mentorship, visual storytelling, and progress loss. The preliminary assessment of a within-subject experiment (pre-test vs post-test) on 60 participants demonstrated that knowledge was improved after the intervention.

**Practical implications** – The game offers an innovative tool for a healthy built environment to educate the general public on mold risks and prevention strategies.

**Social implications** – By promoting healthy housing practices and awareness of indoor environmental quality, the game has the potential to improve respiratory health outcomes and reduce health disparities in vulnerable populations in the built environment.

**Originality/value** – This study represents the first attempt to design, develop, and verify a serious game specifically focused on mold prevention in residential buildings, integrating verified real-world data, expert insights, and user-centered design principles.

**Keywords** Serious game, Raise awareness, Mold, Indoor air quality education, Residential buildings, Storyline 360

**Paper type** Research article

## 1. Introduction

Indoor air pollution poses significant threats to public health (Li *et al.*, 2019). As pollutants accumulate in the air, they contribute to the deterioration of the air quality, leading to a range of adverse effects (Burnett *et al.*, 2018). When the indoor environment lacks proper ventilation or moisture control, it creates a breeding ground for various pollutants such as mold and dust. According to Klepeis *et al.* (2001), people spend more than 85% of their time indoors, with 70% of that time spent in residential settings (Tran *et al.*, 2020). Given this high indoor exposure level, the adverse effects of indoor air pollution become even more concerning. Research by Kankaria *et al.* (2014) indicates that indoor air pollution can be up to ten times more harmful

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than outdoor pollution, making it a critical environmental and public health issue. It is worth noting that indoor air pollution is ranked among the top five environmental risks (EPA, 2023).

One major contributor to indoor air pollution is mold, a fungus that thrives in damp, poorly ventilated environments. When moisture accumulates—whether from leaks, condensation, or high humidity—mold spores can spread rapidly, contaminating surfaces and releasing airborne particles that compromise air quality. Exposure to mold has been linked to various health problems, including allergies, respiratory infections, and asthma exacerbation (Lelieveld *et al.*, 2015; Silva *et al.*, 2017). Vulnerable populations, such as children, older people, and individuals with preexisting conditions, are particularly at risk (WHO, 2019). Addressing mold growth through proper ventilation, moisture control, and early intervention is crucial to maintaining a healthy indoor environment. This emphasis highlights the need for action to prevent mold growth in residential buildings. Educating individuals and raising their awareness about the sources and consequences of mold is vital. Educating people about mold prevention techniques is of paramount importance due to the direct and profound impact it has on human health (Moreira *et al.*, 2022). Understanding these potential health risks empowers individuals to take proactive measures to minimize exposure (Kim *et al.*, 2024).

One promising technique for delivering effective educational content is through gamification (Douglas and Brauer, 2021; Johnson *et al.*, 2016; Feng *et al.*, 2023). Gamification integrates game-like elements, principles, and mechanics into non-game contexts to engage and motivate individuals (Oliveira *et al.*, 2023; Cai *et al.*, 2025). Integrating educational content into interactive and immersive games can enhance people's awareness in an engaging and safe environment (De Jans *et al.*, 2017; Boso *et al.*, 2020; Behl *et al.*, 2024; Schiavi *et al.*, 2022). In the context of gamification, serious design is used to achieve specific educational or training objectives (Laamarti *et al.*, 2014). Serious games are interactive digital experiences designed with the primary purpose of conveying educational or instructional content while engaging users in gameplay (Breuer and Bente, 2010).

While mold is a known problem, there is limited specific research on effective, engaging educational methods, such as serious games, to empower individuals by providing practical skills. Several studies have explored educational interventions for indoor air pollution, focusing on raising awareness about various environmental parameters, such as volatile organic compounds, carbon monoxide (CO), particulate matter (PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>4.0</sub>), ozone, smoke, benzene, and sulfide (Bruno *et al.*, 2020; Campana and Xavier Dominguez, 2020; Mahajan *et al.*, 2020). Much of the research has centered around two primary approaches: raising awareness of air pollution and managing asthma. For instance, Pokric *et al.* (2015) developed a non-immersive serious game for smartphones, which used real-time data monitoring to enhance users' understanding of their exposure to various pollutants. The results were promising, with participants noting the simplicity of the augmented reality development, its usability, and the overall entertainment value of the game.

Similarly, Campana and Xavier Dominguez (2020) aimed to increase senior high school students' awareness of air pollution through an immersive serious game for tablets and smartphones, which integrated real-time PM measurements. In another study, Kim and Sohanchyk (2022) examined a tablet-based application designed for children aged seven to ten years, which used real-time environmental data to raise awareness of indoor air quality. The application garnered positive initial feedback and increased parental involvement. Likewise, Ling *et al.* (2021) studied a smartphone-based serious game incorporating a sensor node for data collection to enhance users' understanding of air pollution. The feedback from participants was encouraging, with 60% of trainees expressing a willingness to continue using the app.

Another significant focus has been on managing asthma through interactive and educational interventions. Studies have explored how serious games can assist individuals, particularly children, in managing their asthma. Thomson *et al.* (2017) investigated children's understanding of asthma clinical outcomes using a serious game integrated into a tablet application that included air quality monitors and spirometers. The results indicated that users

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were more engaged, and children rated the app as fun and somewhat helpful, with the exploration within the game being particularly enjoyable. Similarly, [Grossman et al. \(2017\)](#) developed a smartphone application to promote daily asthma control as a routine behavior. The app educated users about the importance of air quality while integrating a dose-counter spirometer to help track asthma medication usage over time.

In a more targeted approach, [Kim et al. \(2021\)](#) studied children aged eight to twelve years, helping them track their asthma condition and encouraging them to use a spirometer. Their smartphone app, which featured an indoor air quality sensor, customized emojis and characters to trigger motivation, and a history tracker with a chatbot for answering questions, aimed to make asthma management more engaging and personalized. Building on this, [Kim et al. \(2022\)](#) developed a smartphone application that interacted with real-time IAQ data to help users improve their indoor environment and identify asthma triggers. While the app's graphical interface received positive initial feedback, its use declined over time due to a lack of interactivity and fun, highlighting the need for more engaging features to encourage continued usage.

Some studies used digital technologies such as Augmented Reality or Virtual Reality to educate individuals about air pollution. For instance, [Pokric et al. \(2015\)](#) utilized a non-immersive serious game application for smartphones, using real-time data monitoring to teach users about air pollution and its effect on human health. Similarly, [Campana and Xavier Dominguez \(2020\)](#) developed an immersive serious game for tablet or smartphone with real-time PM measurements to increase users' awareness and understanding of air pollution and teach them about potential risks. Regarding the long-term impact and knowledge retention of serious games, [Hu et al. \(2021\)](#) compared medical students who trained using the NEOGAMES serious game against those in a traditional control group. While short-term knowledge gains were limited, results at 6-month follow-up revealed substantially higher retention among participants in the game group, nearly three times the retention compared to controls. Also, [Chittaro and Buttussi \(2015\)](#) demonstrated that an immersive serious game significantly outperformed a traditional safety card in enhancing long-term knowledge retention about aviation safety, with participants maintaining their post-test performance even after one week, highlighting the role of emotional engagement and physiological arousal in sustained learning outcomes.

Although substantial research has been conducted on indoor air quality-related issues, a notable gap exists in mold prevention. Despite the well-documented health risks associated with mold exposure and the widespread nature of the problem, no study has specifically explored the potential of serious games to educate individuals on mold prevention in indoor environments ([Baghaei Daemei et al., 2025](#)). Therefore, this study represents one of the first efforts to address this gap by developing an interactive educational game to educate individuals with practical skills to prevent mold growth in residential buildings.

As such, the primary aim of this study is twofold: first, to prototype a serious game designed to educate people on preventing mold growth in residential buildings, and second, to verify the educational content of the game through a semi-structured interview and home visit investigation. This research presents the practical steps and knowledge required to develop a serious game prototype to raise people's awareness of indoor air quality.

## 2. Methodology

This section outlines the research design, game development process, and evaluation approach.

[Section 2.1](#) describes the development of the serious game prototype, including the tools, technologies, and development process used to create an interactive mold prevention learning experience.

[Section 2.2](#) explains the learning objectives and educational content that guided the game's design.

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[Section 2.3](#) presents the system design, detailing the platform accessibility, visual and audio elements, user interface, and interactive features. [Section 2.4](#) discusses the prototype verification process to ensure alignment between the game's features and the intended learning objectives. [Section 2.5](#) describes the case study, including participant recruitment, data collection procedures, and the instruments used for measuring outcomes. [Section 2.6](#) outlines the analytical methods applied to evaluate the effectiveness of the serious game. The study uses a single-arm experimental design, where participants completed a pre-test, engaged with the serious game, and then completed a post-test. The methodology also includes details about how knowledge was assessed across multiple domains, how responses were scored, and the tools and statistical tests used for analysis.

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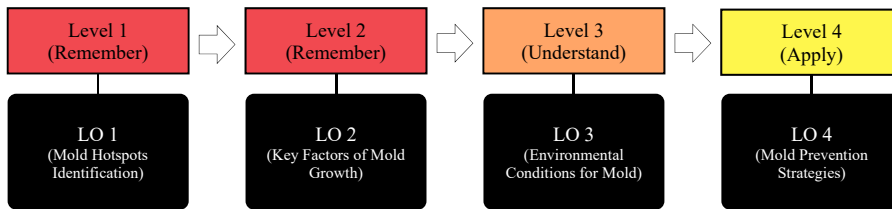
### *2.1 Learning objectives and educational content*

The game has four learning objectives (LOs) designed based on Bloom's Taxonomy ([Krathwohl, 2002](#)), focusing on the first three cognitive levels: Remember, Understand, and Apply. This framework ensures a structured learning progression, guiding players from basic knowledge acquisition to practical application in real-life scenarios. Bloom's Taxonomy levels associated with each learning objective (LO) are presented as follows:

- Remember (LO1 and LO2): The first level of Bloom's Taxonomy involves recalling facts and recognizing key information. LO1 requires players to identify specific spots in the kitchen, bedroom, and bathroom where mold will likely grow, reinforcing memory-based recognition of mold-prone areas. Similarly, LO2 focuses on recalling the essential elements of mold formation—temperature, humidity, spores, and nutrients—helping players establish foundational knowledge of mold growth conditions.
- Understand (LO3): The second level emphasizes comprehension and the ability to explain concepts. LO3 requires players to understand how specific environmental conditions, such as temperature and humidity, contribute to mold growth. This goes beyond memorization by enabling players to connect different factors and predict when and where mold will likely develop.
- Apply (LO4): The third level involves using acquired knowledge in real-world contexts. LO4 focuses on applying strategies to prevent mold growth in residential buildings. This requires players to take what they have learned about mold-prone areas, essential growth factors, and environmental conditions, and translate that knowledge into actionable steps for maintaining a healthier indoor environment.

The target audience for this serious game comprised the general public adults across New Zealand, including homeowners, renters, and individuals living in diverse housing conditions. The game was designed to be accessible to a broad demographic, ensuring ease of use regardless of players' technical skills or prior knowledge of mold prevention. This is supported by several studies reporting that more than half of New Zealand rental houses had visible mold ([Consumer, 2023](#); [BRANZ, 2015](#)).

First, users will learn to identify spots where mold can likely occur (LO1). They will learn the key factors contributing to mold formation (LO2). Additionally, the game will cover the optimal temperature, and humidity ranges necessary to prevent mold growth (LO3). Finally, users will be taught effective strategies for mold prevention (LO4). The learning objectives and educational content were developed based on official public sources, including relevant governmental regulations, standards, building codes, and international publications, as described in the following paragraphs. This ensures that the learning objectives and educational content are aligned with established and evidence-based knowledge rather than general assumptions. Notably, each LO corresponds to each level in the game ([Figure 1](#)). Therefore, users can progress by completing one level after another, advancing their understanding and knowledge about mold prevention.

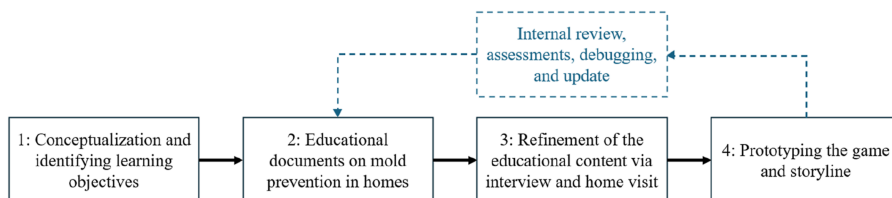


**Figure 1.** The sequence of the levels according to the LOs. Source: Authors' own work

For LO1, the identified zones and spots for potential mold growth include the kitchen, bedroom, and bathroom. In the kitchen, key areas are the kitchen bench (countertop) (Brambilla *et al.*, 2022), windows, and sinks (An and Yamamoto, 2016). In the bedroom, mold-prone spots include windows (Brambilla *et al.*, 2022), walls, and cupboards (wardrobe and closet) (Arumala, 2006; Small, 2003), ceiling corners (Mahooti-Brooks *et al.*, 2004), behind curtains and behind furniture (Stachniewicz, 2018). In the bathroom, common areas for mold growth are window reveals and windowsills (Stachniewicz, 2018; Arumala, 2006), the upper corners of the room (Robbins and Morrell, 2017), carpets and textiles, as well as cooking and laundering areas. For LO2, we found the key components of mold formation, including temperature, humidity, spores, and nutrients, across the published literature (Du *et al.*, 2021; Northolt and Bullerman, 1982). The educational content for LO3 encompasses the optimal ranges of temperature and humidity to prevent mold growth. For optimum occupant comfort and health, a humidity of 40–60% (BRANZ, 2019b; LEVEL, 2023) and an indoor temperature between 18 and 22 °C is recommended (Plagmann, 2019; BRANZ, 2019a; Building Performance, 2023). Finally, for LO4, we identified 15 strategies among several official sources. Among those strategies, we will apply the most practical and effective ones within the game. Public sources in New Zealand suggest several solutions to reduce moisture and condensation. These include wiping condensation off windows and walls and opening windows. It's recommended to avoid using portable gas heaters or unflued gas heaters. Hang washing outside to dry and use lids on pots while cooking. Additionally, fans and rangehoods should be used to ventilate. Limit moisture sources such as fish tanks and indoor plants. Install ventilation systems and use dehumidifiers. Vent driers outside and improve heating and insulation in the house. Pull beds and furniture away from walls, leave wardrobes slightly open, and open curtains during the day (Kāinga Ora, 2023; Allergy New Zealand, 2022; Consumer, 2022; 1News, 2023; Building Performance, 2023).

## 2.2 Serious game prototype development

The prototyping workflow for the serious game adhered to a structured process, as illustrated in Figure 2. It commenced with identifying learning objectives, establishing the core knowledge and skills the game aimed to impart. Subsequently, educational content was developed through a literature review to align with best practices and research findings.



**Figure 2.** The prototyping workflow. Source: Authors' own work

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Thereafter, game mechanisms were designed, incorporating principles from the Octalysis framework. In line with that, some research highlights successful applications of the Octalysis Framework. A study by [Lozano et al. \(2023\)](#) developed a mobile application for mathematical learning, incorporating game-based learning principles with Octalysis-driven mechanics. Evaluations showed improved engagement and effectiveness in knowledge retention. [Mentzelopoulos et al. \(2015\)](#) explored a role-playing simulation platform structured around the Octalysis Framework, providing educators with interactive role-play simulations featuring virtual humans to enhance learning experiences. The results underscored the framework's utility in immersive educational simulations. Furthermore, a classification study on stress management mHealth applications examined how the Octalysis Framework helps map motivational elements in health-related apps, emphasizing user engagement and adherence ([Ewais and Alluhaidan, 2015](#)). The following step involved developing the game's storyline and crafting a narrative reinforcing the learning objectives. Once the structure was in place, the prototype was developed using Storyline 360, translating the conceptual design into an interactive format. This initial version was verified and tested for alignment with learning goals through semi-structured interviews and home-visit investigations. Finally, refinements were made based on verification outcomes, ensuring the game met its intended objectives before final implementation.

*2.2.1 Game mechanics.* To identify the game mechanics, the research team applied the Octalysis Gamification Design Theory principles ([Chou, 2015](#)) to enhance engagement and motivation (see [Table 1](#)). This theory proposes game mechanics aligned with intrinsic and extrinsic motivators, which can engage and motivate players while delivering educational content. The mechanics are designed to ensure players engage with each scene sequentially, requiring them to complete one scene before unlocking the next. This rule guides the player's progression and reinforces learning by gradually introducing more complex challenges and information as they advance through the levels, aligning with the learning objectives discussed in [Section 2.1](#). Reward systems in the game involve incentives, including points and stars that players earn for completing tasks and reaching goals or a certain level. Points are earned for correct choices and deducted for incorrect ones, with a maximum of 10 points and a reduction of 3 points to maintain motivation. Performance is also visually represented through stars awarded at the end of each scene and level ([Figure 3](#)).

Feedback loops in the game provide both instant and overall responses to user actions. Instant feedback appears immediately after each choice, awarding or deducting points, changing hotspot colors (green for correct, red for incorrect), and playing audio cues. Overall feedback is given at the end of each level through a pop-up panel that explains the rationale behind correct and incorrect answers and summarizes the user's final score. For example, in Level 1, hovering over a hotspot reveals a tooltip with its name and image, and selecting it triggers an immediate visual and audio response, reinforcing learning before the next task ([Figure 4](#)).

Also, the feedback gallery serves as the main delivery console and approach for feedback throughout the game (see [Figure 5](#)). After completing each task, users are directed to the feedback gallery, where they can read the rationale behind their choices. This feedback mechanism ensures players understand why certain decisions were correct or incorrect, reinforcing learning. Importantly, users cannot skip this section; each piece of feedback must be read before proceeding. Once all the feedback sections are reviewed, a "Next" button directs players to the next scene, task, or level. This structure ensures that the educational content is delivered equally to all players, guaranteeing they receive the same guidance and understanding before advancing.

The game's narrative revolves around "Mr. Grumpy Moldwell", a virtual assistant who guides the players through the game experience. Mr. Grumpy Moldwell provides essential tips and instructions throughout the game. His guidance is delivered through textual prompts and audio (speech) instructions at a moderate speaking pace to ensure clarity and ease of

**Table 1.** The selected game mechanics incorporated into the game are aligned with the Gamification Design Framework (Octalysis) developed by (Chou, 2015)

CDs	Mechanics	Explanation/Usage
CD 1: Meaning	Narrative	Narrative refers to the storyline and context that immerses players in the learning experience. It integrates characters, scenarios, and challenges that provide a real-world framework for players to explore through a compelling story
	Higher Meaning	It provides players with a sense of purpose beyond the game itself. Players are motivated not just by the game’s rewards, but by the belief that their actions contribute to a greater cause or have real-world significance
CD 2: Accomplishment	Points	Points are a form of extrinsic reward that recognizes player’s actions and achievements
	Progress Bar	The progress bar visually represents how far the player has completed a task or mission
	Quest Lists	Quest lists outline tasks or challenges that guide the player’s journey
	Step-by-Step Tutorial	The tutorial breaks down tasks and teaches the player how to succeed in the game
CD 3: Empowerment	LevelUp	Whenever you level up, you acquire a new set of skills
	Symphony	
	Milestone	It represents a key achievement or significant event in the game that rewards the player with new content and levels. It marks the completion of a specific set of tasks
CD 4: Ownership	Unlock	
	Instant Feedback	The immediate responses players receive based on their actions or decisions in the game
CD 5: Social Influence	Avatar	A customizable digital representation of the player within the game
	Mentorship	It refers to a guidance system where an experienced character (a virtual character) provides the player with advice, support, and knowledge
CD 7: Unpredictability	Visual	This mechanic uses images, animations, and design elements to convey the game’s narrative and themes. Rather than relying on text or dialogue, it communicates key messages, emotions, and ideas through art style, character design, environments, and visual cues
	Storytelling	
CD 8: Avoidance	Progress Loss	It refers to the mechanic where players lose some in-game points after failing the task or challenge

understanding. Guidance will appear as pop-ups before each scene and level, with “Next” and “Back” buttons allowing players to review the instructions as needed (Figure 6).

The game allows for a personalized experience by incorporating an avatar selection feature and a text box where users can input their preferred names. Both the avatar and the chosen name are displayed in the status panel, creating a more engaging experience (Waltemate et al., 2018). Selecting a preferred avatar and typing a preferred name are mandatory steps before proceeding to the next stage of the game. A status panel was included in the top left corner of each scene, displaying the user’s chosen avatar, preferred name, gained scores, progress bar, and the number of tasks they need to accomplish (see Figure 7).

*2.2.2 Narrative and storyline.* Players explore a typical house in New Zealand, focusing on three key rooms: the kitchen, bedroom, and bathroom (see Figure 8). As new residents, users learn how to prevent mold growth through a structured, sequential gameplay experience. The game is divided into four levels, each aligned with a specific learning objective. Players must complete one level before unlocking the next to progress, ensuring a step-by-step approach rather than random access. Each level begins with instructions and tips to guide players, followed by immediate feedback on their choices at the end of each scene.



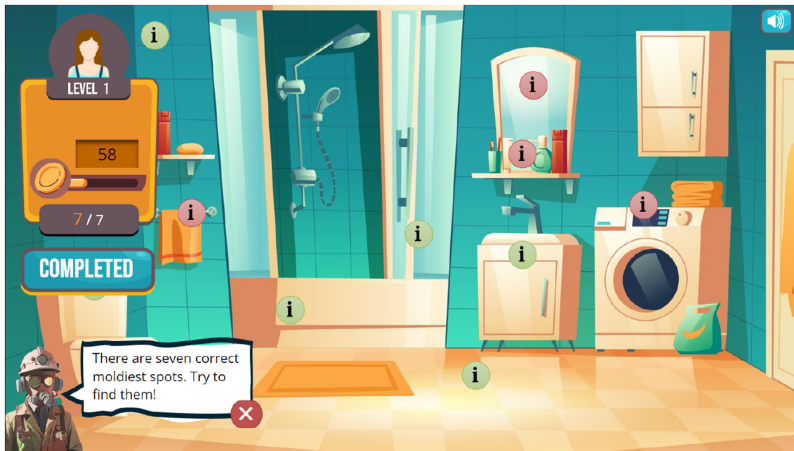
(a)



(b)

**Figure 3.** The in-game reward system. Based on participants' performance and the number of points earned, they receive a rating of one to three stars for each task (a). The total accumulated score is also displayed before advancing to the next level (b). Source: Authors' own work

The game occurs in a realistic setting where players move into a newly acquired New Zealand house at risk of mold growth. After an introductory briefing on mold prevention and the game's goals, players progress through levels representing different rooms, each with specific challenges. They apply knowledge learned in earlier levels to identify mold-prone areas, adjust environmental conditions, and implement prevention strategies. The final level reviews the entire house, requiring players to apply all learned techniques, followed by a performance summary and feedback. The step-by-step structure ensures gradual skill development, while the narrative keeps players engaged by linking decisions to visible



**Figure 4.** Displaying instant feedback for each participant's response by showing a pop-up notification indicating "Right" or "Wrong" for each choice, accompanied by a color change, green for correct answers and red for incorrect ones in the game scene. Source: Authors' own work

outcomes. Designed for independent play, the game integrates all instructions and guidance within the gameplay. Story elements are revealed through dialogue, visual cues, and feedback, with interactive tasks such as selecting hotspots, receiving instant and overall feedback, and tracking scores. This structure combines practical learning with an immersive, scenario-based experience.

Regarding game dynamics and activity types, each level incorporates interactive tasks designed to engage users and reinforce learning. In Level 1, players are presented with hotspots, each containing either a correct or incorrect mold-prone spot. Users must select based on the given scenario, with immediate feedback on whether their choice is correct or incorrect. Upon completing the requested tasks, a "Completed" button will appear under the status panel (Figure 9 left). Users must click on this button to view their overall collected points. They can track their accumulated points from this screen and proceed to the Feedback Loop (Figure 9, right). This action is the same for all levels.

For Level 2, a free-form drag-and-drop activity was designed, consisting of eight correct and four incorrect items. Players must drag and drop the items into the appropriate boxes on the right side of the screen. As each item is placed in the correct or incorrect spot, instant feedback is provided by changing the item's color to green for correct placements and red for incorrect ones. This activity aims to educate individuals by providing immediate feedback rather than testing their knowledge or penalizing them through point deductions for multiple attempts. Additionally, as players place each item, the status panel dynamically updates to reflect the remaining task progress, offering another layer of visual feedback. Once all items have been correctly placed, a Submit button appears in the center of the screen, allowing players to complete the task and review their final feedback. Upon submission, players receive 10 points as a reward for correctly arranging all the items (Figure 10).

In Level 3, the activity is called "Pick One." Users must choose from four groups representing different temperature and humidity conditions, designed as interactive buttons. Users can select only one group and submit their response. If they choose an incorrect group, a dialogue box appears, providing instant feedback on why their choice is incorrect and guiding them to retry until they select the correct group. Once they identify and submit the correct group, they receive 10 points, and another dialogue box appears, explaining the feedback and redirecting them to the next level (see Figure 11).

**CORRECT SPOTS**

- ✓ Windowsill and Frames
- ✓ Ceiling corner
- ✓ All over the ceiling
- ✓ On the shower glass
- Around the shower or bathtub
- On the grout and tiles
- On the interior surface of walls

**FEEDBACK**

Shower glass gets moldy because it's **always damp**, especially if the **bathroom isn't well-ventilated**. **Soap, shampoo, and body oils** leave behind a residue that mold feeds on. **Mold spores** in the air land on the wet glass, and with **enough moisture**, they start to grow.

(a)

**CORRECT SPOTS**

- ✓ Windowsill and Frames
- ✓ Ceiling corner
- ✓ All over the ceiling
- ✓ On the shower glass
- ✓ Around the shower or bathtub
- ✓ On the grout and tiles
- ✓ On the interior surface of walls

**FEEDBACK**

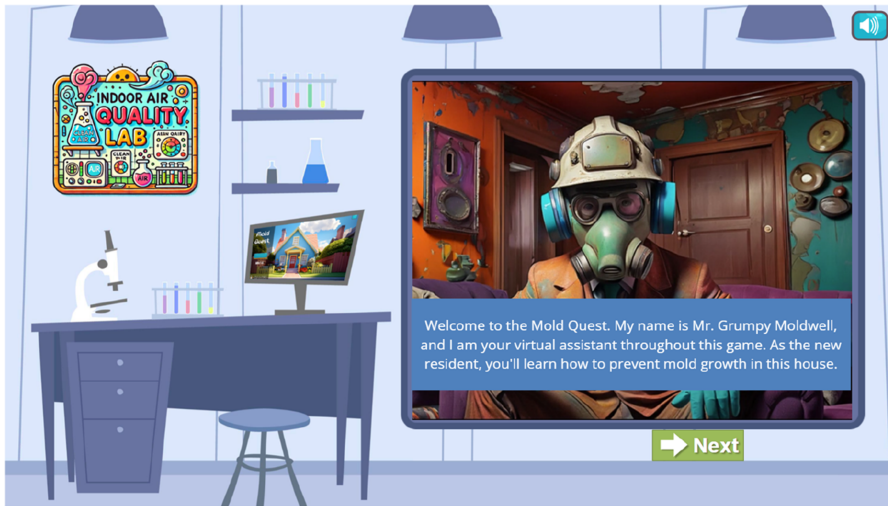
Mold grows on grout and tiles because grout is porous, **trapping moisture and dirt**. Combined with **high humidity and constant dampness** in areas like showers, it creates the perfect environment for mold to thrive.

**NEXT**

(b)

**Figure 5.** After completing each level, participants are redirected to the Feedback Gallery Interface, where they engage with detailed insights about the tasks they have just completed (a). Progression to the next level is conditional upon reviewing all feedback tabs, making this step a mandatory part of the learning pathway (b). Source: Authors' own work

In Level 4, the activity focuses on applying various strategies. Initially, the first scene presents nine strategies, but only one is active at a time, while the others remain disabled. Players must complete each activity sequentially before proceeding to the next one (Figure 12). The activities are designed to align with the nature of each strategy. For example, in the first strategy, opening the window for 15 min daily, players are presented with a bathroom scene where steam appears on the screen. To complete the task, they must click on



(a)



(b)

**Figure 6.** Before each level, the main virtual assistant (“Mr. Grumpy Moldwell”) presents essential tips and instructions to guide participants (a). Once the level begins, contextual hints are provided to support participants in completing each task (b). Source: Authors’ own work

the window, triggering an animation that shows the steam dissipating. Once completed, they can move on to the next strategy.

Strategy 4 is venting the dryer outside, which is an example to elaborate on this task. In this activity, players are presented with a laundry room scene where an uninstalled duct is visible. They fix the ventilation system by placing the duct piece into the highlighted area. Once correctly installed, the system is properly vented, allowing players to progress to the next strategy. Another example is Strategy 5: Better heating and insulating the house. In this activity, players first receive two instructional dialogues explaining the purpose of the task.



**Figure 7.** At the beginning of the game, participants select their preferred avatars and enter their name (a). The Status Panel displays key elements, including the chosen avatar, player name, current level, accumulated points, progress bar, and remaining tasks, which will be shown in the game's primary levels (b). Source: Authors' own work

Then, they are shown a house with pulsating markers on the walls and roof, indicating where insulation needs to be placed. Players apply insulation by clicking on these areas to improve the house's warmth. Upon completing the task, a temperature indicator updates to reflect a warmer indoor environment, and players are rewarded with 10 points before unlocking the following strategy (Figure 12).

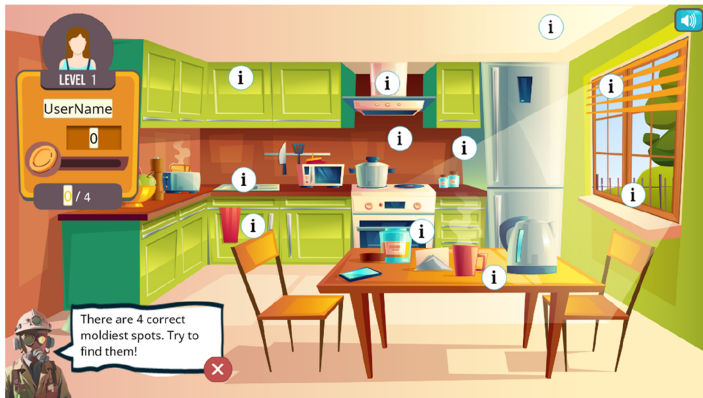
By applying specific mold prevention strategies, users can actively engage in decision-making activities, such as dragging and dropping objects (e.g. placing lids on pots or pulling the bed away from the wall) or interacting with in-game elements (e.g. turning on the rangehood or exhaust fan). As users make decisions, they will see the immediate impact of their actions on the reduction of moisture and mold risk, visually represented by changes in the mold risk and humidity levels. This interactive approach helps reinforce the effectiveness of different strategies in managing indoor environmental conditions to prevent mold growth.

### 2.3 Serious game system design

Storyline 360 provides an easy-to-use design interface while offering powerful interactivity through built-in triggers and the ability to use JavaScript for custom features. In this game, we used if conditions, triggers, and variables to create interactive elements, and JavaScript code to animate the shapes and objects. By combining these tools, the research team built a dynamic experience where the game adapts to the player's decisions, offering immediate feedback and unlocking new content as they move through each level. This tool was key to developing the sequential, task-based structure and implementing interactivity such as clickable areas, feedback systems, and scoring mechanisms. The development followed a waterfall approach, a structured, sequential design model that involves distinct phases such as requirements analysis, design, implementation, testing, and maintenance. This approach ensured a clear and systematic framework for the creation of an educational game focused on mold prevention (Kramer, 2018). Figure 13 illustrates the game story view.

**2.3.1 Platform and accessibility.** The game is accessible on PCs, laptops, tablets, and smartphones, ensuring cross-platform compatibility and broad reach. Designed for independent play, it enables users to progress independently without supervision. All necessary guidance, instructions, and tips are embedded within the gameplay to support users with diverse educational backgrounds and varying levels of experience with digital games. The final product is delivered in HTML format, eliminating the need for installation.

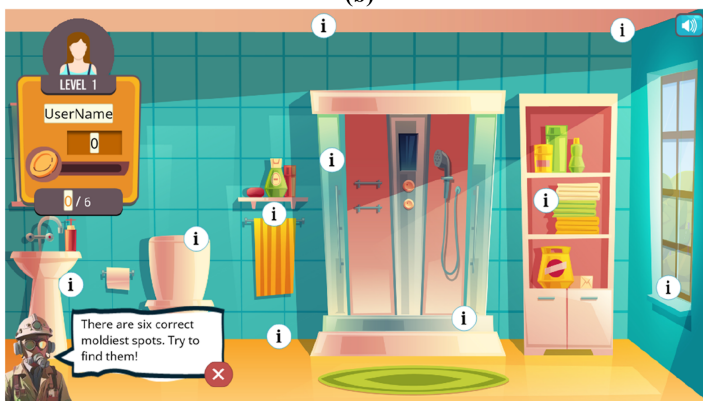
**2.3.2 Visuals and graphics.** The game adopts a 2D cartoon-style design to ensure accessibility for many players, including those with limited experience in complex video



(a)



(b)



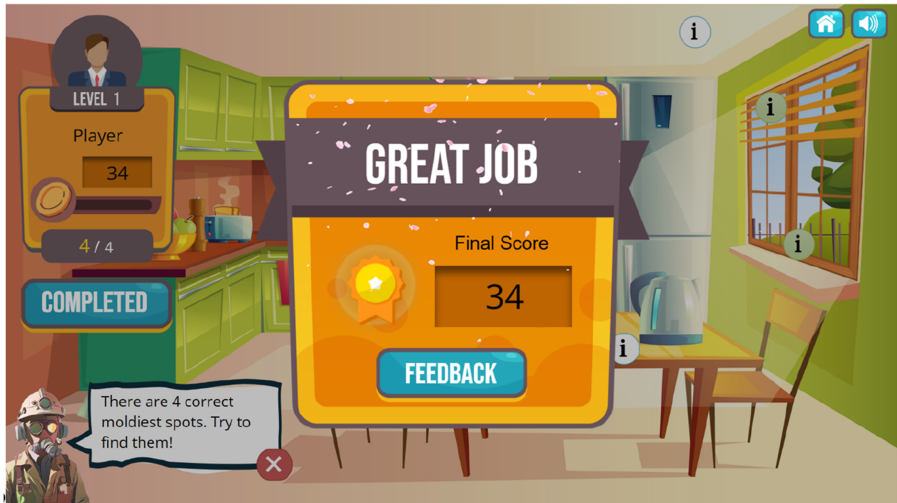
(c)

**Figure 8.** In Level 1, participants are tasked with identifying the moldiest spots within three different environments: the kitchen (a), bedroom (b), and bathroom (c). Each room contains pre-defined, highlighted areas from which participants must make their selections. Source: Authors' own work

games. This visual approach is engaging yet straightforward, providing a clear, easy-to-navigate interface. Images, pop-up elements, and background scenes were sourced from the



(a)

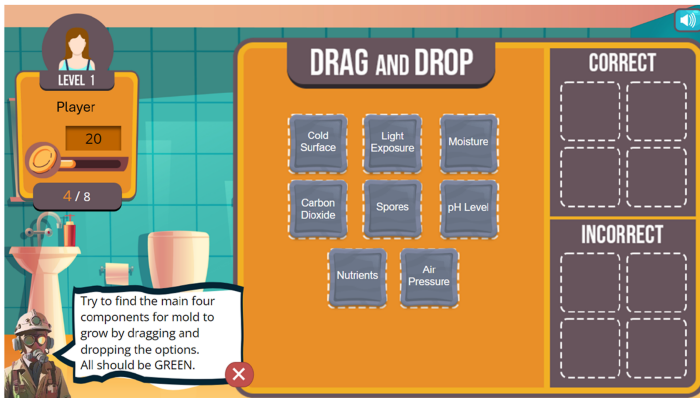


(b)

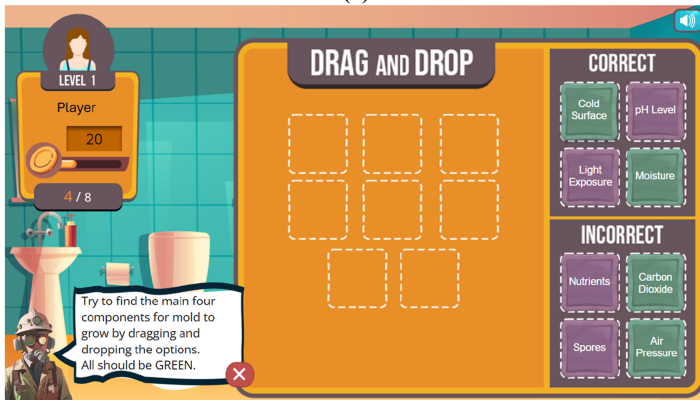
**Figure 9.** Upon completing the assigned task, a “Completed” button indicates task completion (a). Clicking this button triggers a pop-up window congratulating the participant, displaying the score earned, and redirecting them to the Feedback Gallery Interface (b). Source: Authors’ own work

open-access Freepik platform ([www.freepik.com](http://www.freepik.com)) and subsequently customized using Adobe InDesign and Photoshop to align with the game’s aesthetic and educational objectives.

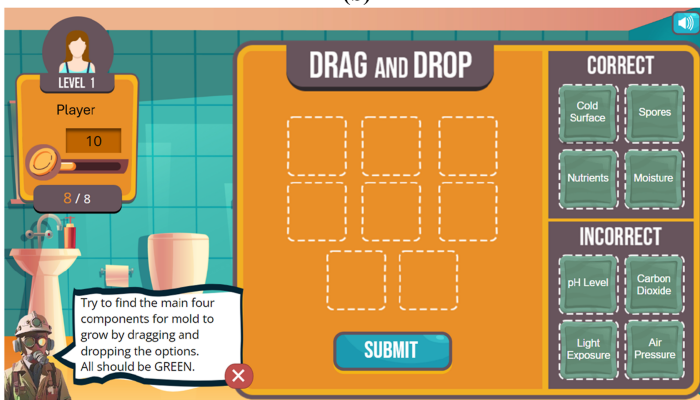
2.3.3 *Audio and sound.* The game incorporates minimal yet effective audio elements, including background sounds to create an immersive environment and sound effects to indicate correct or incorrect responses. These cues reinforce learning and enhance the interactive experience. Voiceovers were produced using the Eleven Labs AI text-to-speech generator ([www.elevenlabs.io](http://www.elevenlabs.io)) to deliver clear, realistic instructions. Mini Movie Maker (Windows version) combined short video clips with the generated audio. Audio is primarily featured in the Indoor Air Quality Lab (left image in [Figure 6](#)), where the virtual assistant, Mr.



(a)

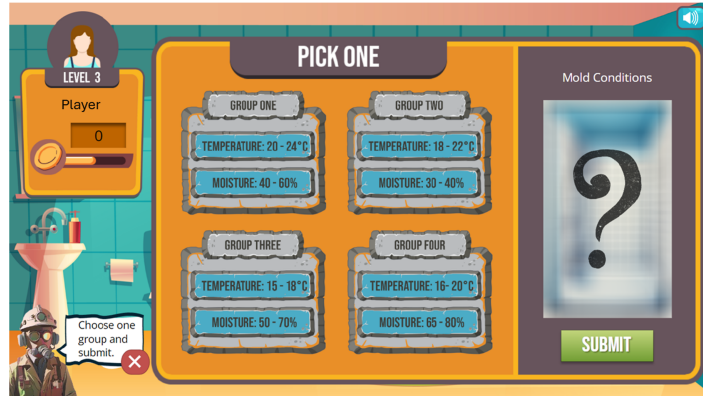


(b)



(c)

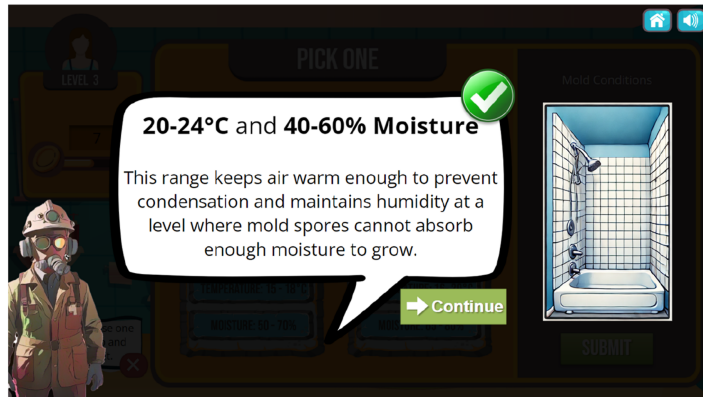
**Figure 10.** Drag-and-drop activity in Level 2 (a). Participants must identify and place the four correct items related to mold formation from a set of eight. Immediate feedback is provided via color changes, green for correct and red for incorrect items (b). Once completed correctly, a “Submit” button appears to confirm their choices and proceed (c). Source: Authors’ own work



(a)



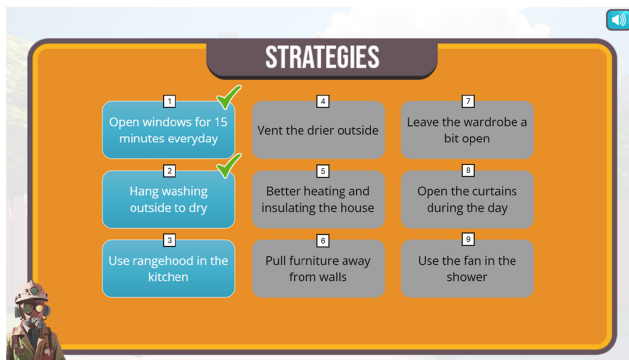
(b)



(c)

**Figure 11.** In Level 3, participants select the appropriate temperature and humidity range from four available groups (a) to prevent mold growth. If the selection is incorrect, participants receive feedback (b and c). They can then retry until the correct group is identified to proceed. Source: Authors' own work

Grumpy Moldwell, provides essential guidance before players enter the interactive scenes. Subtle background music further enriches the atmosphere, with pause and mute options for

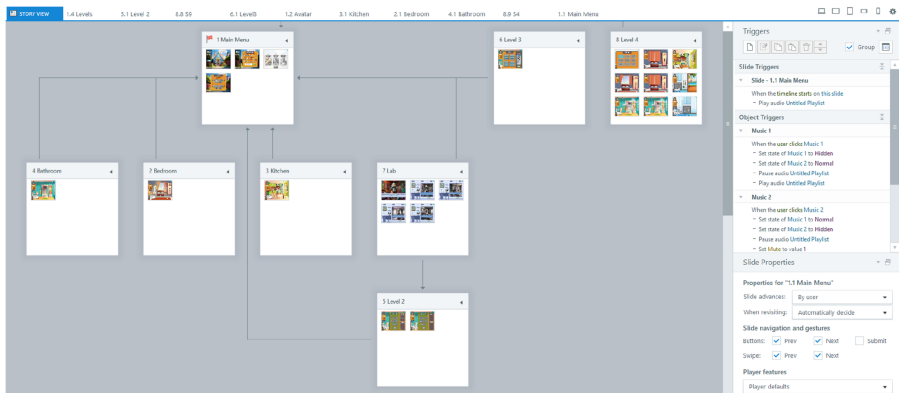


**Figure 12.** Level 4 presents nine essential strategies for preventing mold growth. Participants apply one strategy at a time in sequence; each subsequent strategy becomes available only after the previous one is completed. These pictures depict the strategies from 1 to 9. Source: Authors' own work

user control. Positive sounds are played as players progress when points are earned, while error cues signal point deductions. Upon completing a task, a distinctive accomplishment sound marks the successful completion of the level, providing positive reinforcement and encouraging continued engagement.

**2.3.4 Language and textual information.** The language in the game is simple, with no slang, to ensure it is accessible to international audiences and non-native English speakers. Textual instructions and feedback are designed to be direct, offering step-by-step guidance. The text is presented alongside visual cues, making it easier for users to understand and retain the information.

**2.3.5 User interface and interaction.** The game's user interface (UI) is designed to be intuitive and personalized. Players select an avatar and enter their name, which is displayed throughout the game to maintain engagement and create a stronger connection with the content. A status panel in the top-left corner tracks points, tasks, avatar, name, and progress, serving as a constant guide and providing an overview of achievements and next steps. Gameplay is primarily task-based, with players completing objectives to advance through levels. In Level 1, they identify mold-prone areas in kitchens, bedrooms, and bathrooms by



**Figure 13.** The game story view displays the whole sequence of slides and interactions within the Storyline 360 software. Source: Authors' own work

selecting highlighted spots, earning points for correct choices and losing points for incorrect ones. Level 2 presents multiple-choice questions on key elements required for mold growth. Levels 3 and 4 involve adjusting sliders and applying prevention strategies learned earlier. Each level builds on the previous one, promoting structured progression and reinforcing learning objectives. Interactive mechanics—such as hotspot selection and temperature/humidity adjustments—encourage experimentation and learning through trial and error, supported by a feedback system that immediately responds to player actions.

#### 2.4 Prototype verification on learning objectives

A verification step was conducted after developing a preliminary prototype to ensure the prototype meets design specifications. The verification step involved semi-structured interviews and home-visit observations. In the interviews, the interviewees were presented with the preliminary prototype and gave feedback and comments on the game content. In the home visits, mold-prone areas and cases were investigated in residential buildings, offering real-world context and verification to the game.

**2.4.1 Interview with experts.** The invitation process began with an online invitation via email, with meeting schedules facilitated through the Doodle platform ([www.doodle.com](http://www.doodle.com)). The interviews were held on Microsoft Teams, lasting approximately 40 min for each participant. Video recordings and transcriptions were obtained using Microsoft Teams. NVivo was utilized for coding and thematic analysis, which allowed for an examination of the qualitative data. The research team contacted over 60 IAQ experts in New Zealand via email invitations, with twelve responding and agreeing to participate in the interview. The participants received a detailed participation information sheet outlining the study's purpose, procedures, and ethical considerations. Before organizing the interview sessions, all participants had to sign a consent form, ensuring their informed participation agreement. [Table 2](#) provides the interviewees' demographic information.

[Table 2](#) presents the interviewees' diverse backgrounds, professions, and educational experiences, ensuring that insights were drawn from both industry and academic perspectives. Participants included building advisors, building scientists, university lecturers, housing assessors, sustainability specialists, researchers, architects, and senior technicians. The interview comprised five parts, covering the four learning objectives (LOs) and general game content. In Part 1, participants assessed whether the game accurately represented common mold-prone areas in kitchens, bedrooms, and bathrooms, and suggested additional rooms (e.g. living rooms) or overlooked spots. Part 2 examined the clarity and relevance of the options

**Table 2.** Interviewees' demographics

Category	Subcategory	Percentage (%)
Age	25–34 years	9.1 ( <i>N</i> = 1)
	35–44 years	36.4 ( <i>N</i> = 4)
	45–54 years	27.3 ( <i>N</i> = 4)
	55–64 years	27.3 ( <i>N</i> = 3)
Gender	Female	36.4 ( <i>N</i> = 5)
	Male	63.6 ( <i>N</i> = 7)
Education	Associate degrees	18.2 ( <i>N</i> = 1)
	Bachelor's degrees	18.2 ( <i>N</i> = 3)
	Master's degrees	27.3 ( <i>N</i> = 4)
	Doctoral	36.4 ( <i>N</i> = 4)
Profession	Advisor	8.33 ( <i>N</i> = 1)
	Building Scientist	16.67 ( <i>N</i> = 2)
	Senior Lecturer	8.33 ( <i>N</i> = 1)
	Housing Assessor	8.33 ( <i>N</i> = 1)
	Sustainability Specialist	16.67 ( <i>N</i> = 2)
	Research Scientist	16.67 ( <i>N</i> = 2)
	Architect	8.33 ( <i>N</i> = 1)
	Senior Technician	8.33 ( <i>N</i> = 1)
Experience	1–5 years	9.1 ( <i>N</i> = 1)
	6–10 years	18.2 ( <i>N</i> = 2)
	11–15 years	27.3 ( <i>N</i> = 2)
	Over 16 years	45.5 ( <i>N</i> = 7)

**Source(s):** Authors' own work

provided for mold formation, inviting suggestions for additional information to enhance user understanding. In Part 3, participants evaluated whether the temperature and humidity ranges were realistic and proposed effective communication strategies for preventing mold growth in residential buildings. Part 4 sought input on additional strategies to enhance learners' understanding of mold prevention and the practicality of simulating kitchens, bedrooms, and bathrooms for users to apply these strategies. Finally, Part 5 explored the game's overall strengths and key takeaways, allowing participants to share further insights or recommendations not addressed in earlier questions.

*2.4.2 Home-visit investigation.* The home-visit investigation consists of visiting six homes to validate the content collected from the interviews. A key component of the visit involved capturing photographs of mold-prone areas in residential buildings to validate the results collected through the interview. Participants were recruited through a door-to-door approach in Auckland, New Zealand, where homeowners were asked if they had experienced mold in their houses. These homes were selected based on their varying ages, construction materials, and ventilation system levels to provide a representative understanding of mold-prone conditions. Only standalone houses were considered for this study. Participants were fully informed of the research purpose, and their written consent was obtained before data collection. Photographs did not include identifiable features. After capturing the pictures, participants were contacted via email to confirm the use of the images in the research. After capturing the photographs, the findings were compared with the interview results to validate the accuracy and consistency of the reported mold issues.

### *2.5 Case study: participants and data collection*

This case study was designed to evaluate the effectiveness of a game-based learning approach for mold prevention education in residential buildings. The study targeted members of the

general public in New Zealand and employed a single-arm experimental design with three stages of data collection: pre-test and post-test. The primary aim was to assess how a game-based learning experience influenced knowledge acquisition. A set of validated instruments was employed to determine the key constructs of the study and ensure methodological rigor. The questions are provided in [Appendix](#).

*2.5.1 Participant recruitment and sampling.* The prototype was tested with the general public in the Auckland region. A non-probabilistic convenience sampling strategy was adopted to recruit 60 participants. Recruitment was conducted through flyers and word of mouth. Diversity in age, household type, and socio-demographic background was considered during recruitment to enhance the ecological validity of the study. All individuals received an information sheet and signed an informed consent form before participation. Participants received a \$10 (NZD) supermarket voucher upon study completion to acknowledge their contribution. A detailed breakdown of participant demographics, including gender, housing type, and video game frequency, is provided in [Table 3](#). [Figure 14](#) depicts participants participating in the experimental session, including game and video-based learning groups. Notably, four participants failed the attention check in answering post-test questionnaires, resulting in 56 participants valid for the data analysis.

**Table 3.** Sample demographics

Parameter	Game group (n = 56) #	%
<i>Gender</i>		
Man	23	41%
Woman	33	59%
<i>Type of house</i>		
Apartment/Flat	14	25%
Standalone house	27	48%
Townhouse	15	27%
<i>Frequency of playing video games</i>		
Never	11	20%
A few times a year	16	28%
A few times a month	14	25%
A few times a week	9	16%
Everyday	6	11%

**Source(s):** Authors' own work



**Figure 14.** Participants engaging in a game session during the experiment. Source: Authors' own work

**2.5.2 Data collection procedures.** A single-arm experimental design was employed to assess the effectiveness of this serious game on knowledge. Participants completed a structured pre-test questionnaire measuring their baseline knowledge. Immediately after playing the game, a post-test assessed their knowledge acquisition. An open-ended questionnaire was used to evaluate participants' knowledge across four mold-related domains: (1) identifying mold-prone areas, (2) understanding conditions necessary for mold growth, (3) recognizing optimal temperature and humidity ranges for prevention, and (4) recalling mold prevention strategies. Responses were manually scored. Participants received one point for each correct item mentioned—up to 4 points for kitchen spots, 5 for bedroom, 6 for bathroom (Module 1); 4 points for key mold growth conditions (moisture, cold surfaces, nutrients, spores) in Module 2; 2 points for correct temperature (20–24 °C) and humidity (40–60%) in Module 3; and up to 9 points for prevention strategies in Module 4. The total possible score was 30. This scoring method was consistently applied across the pre-test, post-test, and retention test. The data were collected digitally via Qualtrics.

**2.5.3 Data analysis.** Inferential statistical analysis was conducted to assess the effectiveness of game-based learning. This analysis aimed to determine whether the observed differences between the pre-test and post-test were statistically significant. First, the dataset was screened for completeness to remove invalid or incomplete responses. The post-test questionnaire included an attention check question: “*I will answer this questionnaire seriously, so for this question I will choose DISAGREE*”. Participants who selected any response other than “Disagree” were considered to have failed the attention check, resulting in the exclusion of their data. Consequently, 4 out of the 60 responses were eliminated from data analysis.

Second, the normality of each outcome variable was assessed using the Kolmogorov-Smirnov test (Razali and Wah, 2011), supported by visual inspections such as histograms and plots. The test indicated that the responses for each measurement were not normally distributed. Therefore, the Wilcoxon signed-rank test was used to test the significance between groups. Third, a single-arm experiment (e.g. pretest vs. posttest) was conducted using the Wilcoxon signed-rank test when data violated normality assumptions. This non-parametric approach was chosen to appropriately assess changes over time within each intervention group for paired samples. Lastly, the effect size was calculated to evaluate the magnitude of observed differences in knowledge acquisition. Cohen's *d* was determined by dividing the mean of the differences by the standard deviation of the differences from paired samples:  $Cohen's\ d = M_{Difference} / SD_{Difference}$  (Dankel and Loenneke, 2021). All statistical analyses were performed using IBM SPSS Statistics Version 30.

### 3. Results

#### 3.1 Interview findings

This section presents the experts' feedback on each learning objective (LO). A total of 12 experts (E1–E12) were consulted, and their responses were analyzed by counting how many supported or rejected each item. The questions focused on three main indoor environments: kitchen, bedroom, and bathroom.

To make the analysis consistent, a binary scoring system was used:

- (1) 1 if an expert recommended the strategy
- (2) 0 if they did not recommend it

The scores for each strategy ranged from 0 to 12, showing how many experts agreed. Based on the number of approvals, strategies were grouped into three categories:

- (1) Highly Recommended – 10 or more approvals
- (2) Moderately Recommended – 4 to 9 approvals
- (3) Less Recommended – 3 or fewer approvals

3.1.1 Mold hotspots identification (LO1). First, the interviewees were told about the aim of LO1. Then, three slides were shown to them in which the highlighted hotspots were visible, including the correct and incorrect spots (Figure 15). The interviewees were asked to share their opinion regarding the highlighted correct hotspots. The interviewees agreed that certain

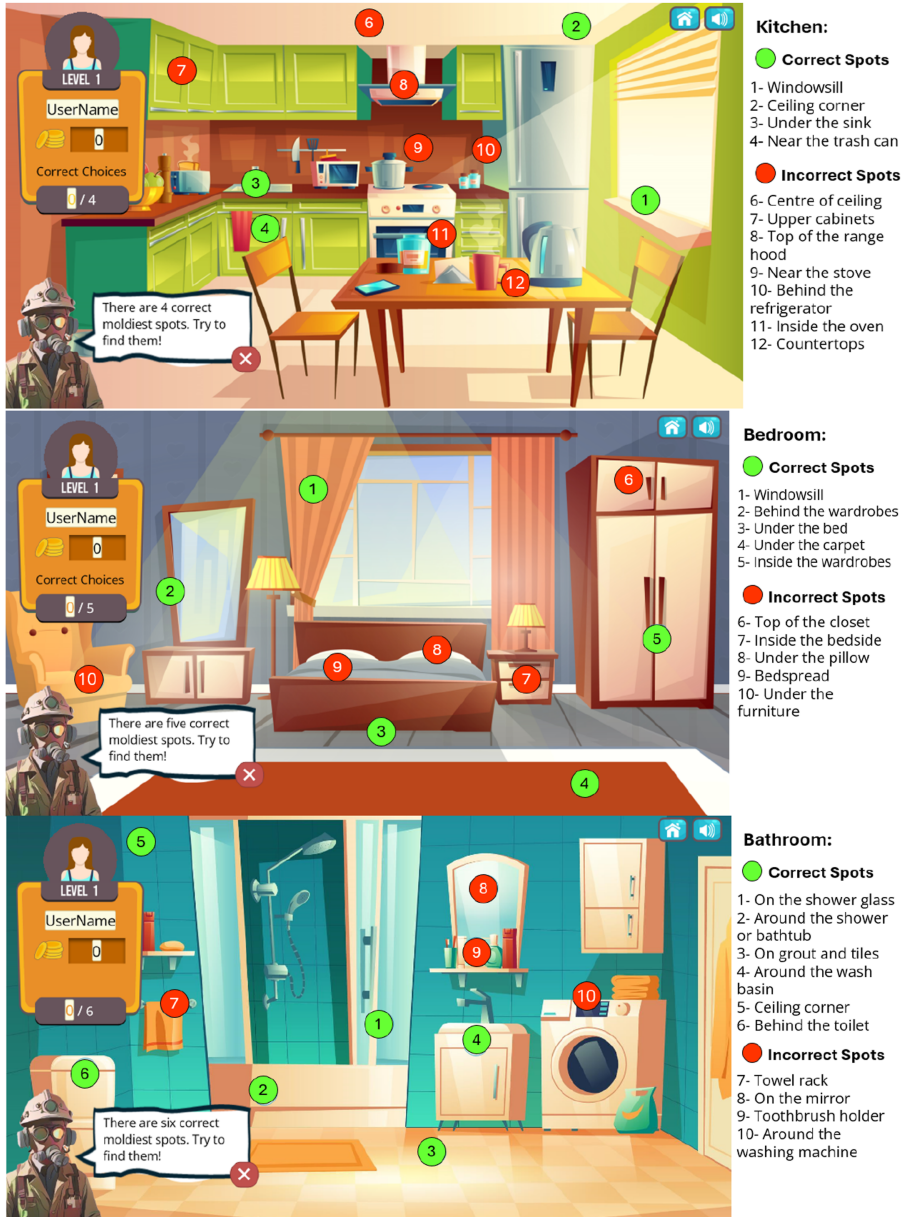


Figure 15. Sample slides were presented during the interview to gather expert input on the moldiest spots in the kitchen, bedroom, and bathroom. Source: Authors' own work

spots in each room were more likely for mold to grow. In the kitchen, the windowsill was highlighted as a high-risk area. Similarly, the windowsill was identified as the most susceptible spot for mold in the bedroom. In the bathroom, the interviewees pointed out multiple regions, including the shower glass, around the shower or bathtub, grout and tiles, and behind the toilet, as the most likely locations for mold growth. Table 4 provides further details on interviewees' responses and recommendations.

Several participants highlighted specific locations as particularly vulnerable to mold growth, often linked to moisture accumulation and poor air circulation. For example, one expert noted, "Windowsill definitely . . . you could get it on the glass as well," while another explained, "Ceiling corner — most likely to get mold there if insulation is missing." Hidden or less obvious areas were also mentioned, such as "behind the dresser, especially if it is an old building," and "behind the curtains," where condensation can accumulate. Bathroom areas were frequently cited, with one expert describing, "If it is an old one, like a shower above the bath . . . definitely on grout and tiles, and around the wash basin." Although some locations were considered less likely, such as "inside the oven, definitely not" or "top of the washing machine, all pretty unlikely," the expert consensus emphasized that mold-prone areas often have poor ventilation, high humidity, or persistent dampness.

The interviewees expressed several opinions regarding mold risk and building design. They noted that areas under the sink are less likely to get moldy unless there are leaks or if they are located near the trash can. Additionally, they suggested including curtains as a potential factor in each room's mold prevention strategy. Seven interviewees recommended separating the laundry from the bathroom, proposing the development of a dedicated laundry room. Furthermore, they suggested incorporating windows into the bathroom since there was no window in the initial version of this room. In kitchens, three interviewees suggested fruits inside the refrigerator or on countertops as potential mold-prone items. Ceiling corners, particularly those far from heat-producing appliances like refrigerators, were also often mentioned. This is because the heat from refrigerators helps prevent mold from growing near

**Table 4.** Common moldy spots in homes, according to the literature

Rooms	Spots	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
Kitchen	1-Windowsill	×	×	×	×	×	×	×	×	×	×	×	×
	2-Ceiling corner		×		×							×	
	3-Under the sink						×			×			
	4-Near the trash can					×						×	
Bedroom	1-Windowsill	×	×	×	×	×	×	×	×	×	×	×	×
	2-Behind the wardrobes		×	×	×					×			×
	3-Under the bed						×						
	4-Under the carpet				×								
	5-Inside the wardrobes	×	×	×		×			×		×	×	
Bathroom	1-On the shower glass	×	×	×	×	×	×	×	×	×	×	×	×
	2-Around the shower or bathtub	×	×	×	×	×	×	×	×	×	×	×	×
	3-On the grout and tiles	×	×	×	×	×	×	×	×	×	×	×	×
	4-Around the wash basin									×	×		
	5-Ceiling corner				×								
	6-Behind the toilet	×	×	×	×	×	×	×	×	×	×	×	×

**Source(s):** Authors' own work

them. Curtains, particularly in bedrooms, were another commonly suggested mold-prone area, along with ceiling corners across all three rooms. Some interviewees noted that furniture near exterior walls, such as bed headboards, is susceptible to mold growth.

**3.1.2 Key factors of mold growth (LO2).** For this learning objective, the discussion focused on the reasons for mold formation in homes in New Zealand and the current situation. Participants were presented with a list of key elements contributing to mold growth and asked whether any items should be added or removed. All participants agreed that humidity, temperature, nutrients, and spores are essential to mold formation. However, several experts raised concerns that the terminology might be too technical for a general audience. Most recommended replacing “humidity” with “moisture” and “temperature” with “cold surface” to improve clarity and accessibility. One participant also noted that including CO<sub>2</sub> and air pressure as “incorrect” options might confuse non-specialist users, as these concepts are less familiar to the public.

**3.1.3 Environmental conditions for mold (LO3).** For this learning objective, the discussion began with an overview of the temperature and humidity levels outlined in national standards and regulations for healthy indoor environments. Experts agreed that the optimal indoor temperature range should be between 18 °C and 22 °C, aligning with widely accepted comfort and health guidelines. Initially, the project team proposed an optimal relative humidity range of 35–55%. However, through the interviews, participants recommended revising this to 40–60%, explaining that keeping humidity consistently below 60% is often challenging, particularly in Auckland’s humid climate. This adjustment reflects both practical experience in local housing conditions and the need to present learners with realistic, achievable targets for mold prevention.

**3.1.4 Mold prevention strategies (LO4).** The analysis revealed that four strategies (S2, S4, S6, and S15) were unanimously endorsed by all 12 experts, making them the most critical for mold prevention. These strategies include opening windows daily (S2), hanging washing outside to dry (S4), and using fans and rangehoods (S6). These strategies should be prioritized in awareness campaigns and intervention programs, given their universal acceptance. A second tier of strategies, including opening curtains during the day (S14), using a ventilation system (S8), leaving wardrobes slightly open (S13), venting dryers outside (S10), and pulling furniture away from walls (S12), received moderate agreement from 4 to 6 experts. These strategies may be beneficial in specific contexts, such as homes with limited natural ventilation or insulation issues. Finally, strategies with low endorsement ( $\leq 3$  experts), such as wiping condensation off windows (S1), limiting moisture sources (S7), and using dehumidifiers (S9), were less frequently recommended. These strategies may hold value but could be considered secondary measures or dependent on specific household conditions (Table 5).

As part of the final interview stage, the participants were also asked whether spaces beyond the kitchen, bedroom, and bathroom should be included in the game, such as lounges or garages. Most agreed that the current focus on these three spaces was appropriate, as areas like living rooms or garages are often too generic. Lastly, participants were asked whether developing only bedrooms and bathrooms to apply the strategies would benefit users. Universally, participants endorsed this approach, emphasizing the critical importance of bathrooms as one of the most mold-vulnerable home spaces.

### 3.2 Home visit findings

This section presents an overview of the key specifications of the investigated homes, focusing on mold presence in different areas and its correlation with construction type, house age, and location. As part of this research, six standalone homes across New Zealand were investigated to assess mold growth in different areas of residential buildings, each exhibiting varying degrees of mold contamination. Notably, mold was observed in kitchens, bathrooms, and bedrooms, with severity depending on structural characteristics and ventilation conditions. Table 6 provides further specifications of the homes investigated.

**Table 5.** The strategies for mold prevention in homes

Strategies (Ss)	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
S1: Wipe condensation off windows and walls		×		×								×
S2: Open windows for 15 min every day	×	×	×	×	×	×	×	×	×	×	×	×
S3: Avoid using portable gas heaters/unflued gas heaters			×				×					
S4: Hang washing outside to dry	×	×	×	×	×	×	×	×	×	×	×	×
S5: Use lids on pots when cooking	×	×		×						×		
S6: Use a rangehood in the kitchen	×	×	×	×	×	×	×	×	×	×	×	×
S7: Limit sources of moisture, such as fish tanks and indoor plants										×		
S8: Use the ventilation system	×		×				×		×			×
S9: Use dehumidifiers	×	×	×					×				
S10: Vent dryers outside		×	×	×	×	×	×					×
S11: Better heating and insulation of the house	×	×	×	×	×		×	×		×	×	×
S12: Pull beds and furniture away from the walls	×	×		×	×	×	×	×		×	×	
S13: Leave wardrobes a bit open	×			×	×	×					×	×
S14: Open the curtains during the day	×	×	×		×		×		×	×	×	×
S15: Use fans in the shower	×	×	×	×	×	×	×	×	×	×	×	×

**Source(s):** Authors' own work





The findings indicate that bathrooms are the most vulnerable areas for mold growth due to their constant exposure to moisture, steam, and often limited ventilation. On the other hand, kitchens generally exhibit lower mold presence. In bedrooms, mold is frequently observed in areas with poor insulation or heating, particularly on window surfaces and cold exterior walls where condensation accumulates. Some homes (e.g. H4, H5, H6) showed extensive mold growth across large surfaces, particularly in bathrooms, where moisture levels remain consistently high. In H4, mold covered the entire walls and ceiling, indicating severe humidity issues.

### 3.3 Finalized version of the learning objectives

The verification results provided valuable insights that directly shaped the serious game's design, features, and learning objectives. The finalized version of LOs incorporates several changes based on the verification results. Further details are provided in [Tables 7 and 8](#). The bathroom scene was also modified to show the overall ceiling, incorporating a window, based on experts' opinions ([Figure 16](#)).

The findings reflect experts' suggestions regarding recommended temperature and humidity ranges. Specifically, the temperature was changed to 20–24 °C, rather than the earlier suggested 18–22 °C, to maintain a warmer indoor environment and prevent condensation. Similarly, the humidity range was adjusted to 40–60%, rather than 35–55%, based on expert recommendations. Also, the game emphasizes practical strategies to prevent mold growth, including opening windows for at least 15 min every day, hanging laundry outside to dry, using a rangehood in the kitchen, venting dryers outside, improving heating and insulation, pulling beds and furniture away from walls, leaving wardrobes slightly open, opening curtains during the day, and using fans in the shower. These strategies were selected based on expert recommendations ([Table 8](#)).

**Table 6.** Summarizing the key specifications of the investigated homes

Home ID	Location	Housing Type	House Age (Years)	Construction Type	Mold Presence	Spot(s)	Pictures
H1	Takapuna, Auckland	Standalone house	25	Timber-Framed	Kitchen	Windowsill and frames	
H2	Mount Eden, Auckland	Standalone house	20	Brick	Kitchen	Windowsill and frames	
H3	Northcote, Auckland	Townhouse	15	Timber-Framed	Bathroom	Around the wash basin	
H4	Albany, Auckland	Standalone house	20	Concrete Block	Bathroom	All over the ceiling and the inner side of the walls	
H5	Albany, Auckland	Standalone house	30	Timber-Framed	Bedroom and Bathroom	Behind the dresser/closet and all over the ceiling	
H6	Albany, Auckland	Townhouse	22	Timber-Framed	Bedroom and Bathroom	Window frames, the inner side of the walls, all over the ceiling, on grout and tiles, and the inner side of the walls	

**Source(s):** Authors' own work

Consequently, the validation process confirmed that the game content accurately reflects real-world experiences. Expert feedback highlighted actionable strategies, such as briefly opening windows each day or venting dryers to the outside, which have been incorporated into the game. This ensures the content is theoretical and firmly rooted in everyday practicality.

*3.4 Summary of the experimental findings*

Knowledge scores for participants were analyzed across two time points: before the learning experience (Pre-test) and immediately after (Post-test). Using a box plot, [Figure 17](#) illustrates the participants' knowledge scores before and after the learning. A Wilcoxon signed-rank test was conducted to compare knowledge scores before and after the game-based learning intervention. The analysis revealed a statistically significant increase in knowledge scores from pre-test ( $M = 4.14$ ,  $SD = 2.19$ ) to post-test ( $M = 16.21$ ,  $SD = 4.86$ ),  $Z = -6.514$ ,  $p < 0.001$ . All participants ( $N = 56$ ) showed higher scores post-intervention, with no negative ranks or ties, indicating a consistent improvement across the sample. This result suggests that the game-based learning condition substantially positively affected participants' knowledge.

**Table 7.** The final selected moldy spots compared with the literature

Rooms	Literature	Verification results (finalized)
Kitchen	1-Windowsill	1-Windowsill and frames
	2-Ceiling corner	2-On the curtains
	3-Under the sink	3-In the cabinets
	4-Near the trash can	4-Around the trash can
Bedroom	1-Windowsill	1-Windowsill and frames
	2-Behind the wardrobes	2-On the curtains
	3-Under the bed	3-Inside the wardrobes
	4-Under the carpet	4-Behind the wardrobes
	5-Inside the wardrobes	5-Behind the dresser
Bathroom	1-On the shower glass	1-Windowsill and frames
	2-Around the shower or bathtub	2-On the curtains
	3-On the grout and tiles	3-Ceiling corner
	4-Around the wash basin	4-All over the ceiling
	5-Ceiling corner	5-On the shower glass
	6-Behind the toilet	6-Around the shower or bathtub
		7-On the grout and tiles

**Source(s):** Authors' own work

**Table 8.** The final strategies according to the experts' feedback

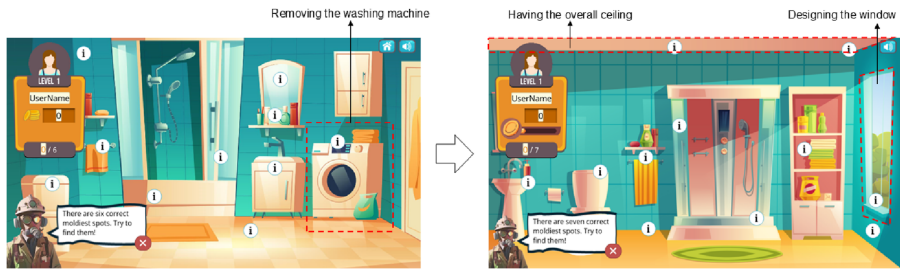
Literature (initial version)	Experts' opinion (refined version)
<ul style="list-style-type: none"> <li>• Wipe condensation off windows and walls</li> <li>• Open windows for 15 min every day</li> <li>• Avoid using portable gas heaters/unflued gas heaters</li> <li>• Hang washing outside to dry</li> <li>• Use lids on pots when cooking</li> <li>• Use a rangehood in the kitchen</li> <li>• Limit sources of moisture, such as fish tanks and indoor plants</li> <li>• Use a ventilation system</li> <li>• Use dehumidifiers</li> <li>• Vent dryers outside</li> <li>• Better heating and insulation of the house</li> <li>• Pull beds and furniture away from walls</li> <li>• Leave wardrobes a bit open</li> <li>• Open the curtains during the day</li> <li>• Use fans in the shower</li> </ul>	<ul style="list-style-type: none"> <li>• Open windows for 15 min every day</li> <li>• Hang washing outside to dry</li> <li>• Use a rangehood in the kitchen</li> <li>• Vent dryers outside</li> <li>• Better heating and insulation of the house</li> <li>• Pull beds and furniture away from walls</li> <li>• Leave wardrobes a bit open</li> <li>• Open the curtains during the day</li> <li>• Use fans in the shower</li> </ul>

**Source(s):** Authors' own work

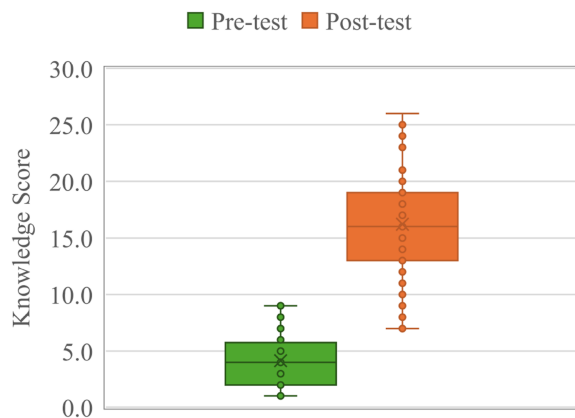
Cohen's d for pre-post difference was computed as 2.74, indicating a significant effect on the game-based learning for knowledge acquisition.

#### 4. Discussion

The main objectives of this study are to develop a prototype of a serious game aimed at educating individuals on preventing mold growth in residential buildings and to verify the educational content of the game. To achieve this, a detailed step-by-step development process was outlined. Educational content was gathered through multiple stages, including reviewing reliable websites and national building codes in New Zealand, conducting semi-structured interviews with experts, and performing home-visit investigations to provide solid evidence of



**Figure 16.** Comparison between the initial version of the scene and the updated version, revised based on expert feedback and featuring a ceiling with an incorporated window. Source: Authors' own work



**Figure 17.** Participants' knowledge scores before the learning (Pre), and after the learning (Post). Source: Authors' own work

mold-prone areas. The findings of this study highlight the need to prioritize mold prevention strategies for specific areas in residential buildings based on their unique environmental conditions. Bathrooms emerged as the most critical spaces due to their high humidity, frequent water exposure, and often limited ventilation. Bedrooms, however, pose distinct challenges, with condensation on windows, cold walls, and poor ventilation contributing to mold growth, particularly in homes with inadequate insulation or heating.

While previous studies (Shabanabegum *et al.*, 2021; Kim *et al.*, 2021, 2022; Kim and Sohanchyk, 2022; Fernandes *et al.*, 2023) This research has focused on general air pollution; it uniquely integrates hands-on strategies for mold prevention, bridging a critical gap in the existing literature. A comparison between the game mechanics selected in this study and those identified in previous research focused on IAQ reveals both similarities and key differences. For example, Pokric *et al.* (2015) used mechanics such as points, leaderboards, and avatars to educate professional employees about air pollution and its effects on human health. Other mechanics included narrative, level progression (LevelUp), quest lists, step-by-step tutorials, instant feedback, progress bars, avatar customization, progress loss, and a visual storyline. Positive feedback highlighted the simplicity of the augmented reality development, usability, and available features, while the game was also deemed entertaining. However, feedback indicated the need for additional tutorials to enhance user engagement.

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Also, [Fernandes et al. \(2023\)](#) utilized similar mechanics, such as narratives, quest lists, step-by-step tutorials, points, instant feedback, and group quests, to improve IAQ knowledge among elementary school children. Their results showed a 50% improvement in knowledge. Satisfaction, usability, and user preferences were also assessed through questionnaires, although technical issues related to AR implementation were reported, particularly with marker tracking. [Relvas \(2021\)](#) employed mechanics such as narratives, quest lists, step-by-step tutorials, and visual storytelling to raise awareness about air pollution and help elementary students understand its possible causes. This comparison suggests that building on the mechanics used in previous studies could lead to positive outcomes. The post-assessment results indicated a significant improvement in the children's perception of air pollution, highlighting the effectiveness of these game mechanics in enhancing learning and awareness.

Several studies have focused on the usability and engagement of gamification applications. For instance, [Alarcon et al. \(2025\)](#) evaluated a serious game designed for teacher training in environmental sustainability. The study used the System Usability Scale to assess the platform's user-friendliness. Results showed a moderate SUS usability score, indicating acceptable levels of ease of use. Importantly, participants reported that gamification elements, such as feedback and reward mechanisms, significantly enhanced their motivation and engagement and supported competency development in scientific inquiry. [Nadeem et al. \(2023\)](#) evaluated a game-based quiz embedded in undergraduate courses using leaderboard mechanics. They found that digital game-based learning significantly boosted student engagement and motivation compared to traditional online quizzes. This demonstrates that thoughtfully designed digital quizzes can meaningfully enhance usability and engagement in higher-education learning environments.

[Kayyali et al. \(2021\)](#) investigated a digital serious game integrated into healthcare education, focused on playability and user perceptions. Participants praised the game's clear learning objectives, intuitive interface, and story-driven progression, contributing to sustained engagement during practical use. These findings highlight that, beyond core usability, narrative structure and straightforward task design are essential for maintaining user focus and instructional efficacy. Similarly, [Espinosa-Curiel et al. \(2020\)](#) developed a nutrition-focused video game for children aged 8–10 years. Their findings strongly link usability factors (challenge, narrative, visual aesthetics) and learning outcomes. They also found that enjoyment and user-experience satisfaction positively correlated with posttest knowledge. Regression analysis confirmed these usability dimensions as significant predictors of knowledge gain.

Contrary to concerns about over-gamification, recent literature suggests that multiple, well-integrated mechanics can coexist without undermining usability. [Magylaité et al. \(2022\)](#) synthesized findings from over 100 gamified systems and identified that combining mechanics like progress indicators, feedback, and rewards, when designed with learnability in mind, maintains usability and enhances engagement. Likewise, [Ghai and Tandon \(2023\)](#) used structural equation modeling to show that the interplay of game elements, dynamics, and instructional design measurably improves usability in e-learning systems. [Lassaad and Yamani \(2024\)](#) demonstrated a 25% increase in engagement and 30% improvement in motivation/performance from using points, badges, leaderboards, and challenges, with no usability detriment.

The data analysis of knowledge acquisition using a between-subject experiment on 60 participants demonstrates that knowledge significantly improved from pre-test (before playing the game) to post-test (after playing the game), which is statistically confirmed. Although this study does not include direct usability testing, the design of the prototype was informed by findings from a prior systematic literature review conducted by the authors, which synthesized user feedback and usability concerns reported in similar serious games focused on air quality ([Baghaei Daemei et al., 2025](#)). These insights guided our game mechanics, user interface, and motivational strategies decisions.

## 5. Conclusion

This study explored developing and evaluating a serious game aimed at enhancing public knowledge on mold prevention in residential settings. The game was designed using a structured framework aligned with Bloom's Taxonomy and evidence-based mold prevention strategies. Through a single-arm experimental design, results indicated that the serious game significantly improved participants' knowledge across various mold-related domains. Integrating gamified elements such as immediate feedback, reward systems, and interactive challenges contributed to learner engagement and knowledge acquisition. Overall, the findings support the potential of serious games as effective tools for environmental health education and behavioral change in the built environment. This study has some limitations. First, the verification step overlooked gameplay and game mechanisms, since only IAQ experts were involved in interviews to examine educational content. Second, this study does not include a validation step to assess the effectiveness and user experience of the game.

This game can be scaled by deploying it as a lightweight HTML5 package with SCORM/xAPI integration, allowing delivery through learning management systems or public web hosting for access across devices. Its modular design, with externalized text and audio, enables rapid localization, cultural adaptation, and the addition of new modules or learning scenarios. Distribution through public health, education, and professional training channels, supported by integrated analytics, allows expansion from small pilots to large-scale national or international use. Language translation and localization enable the game to reach a broader audience and adapt to diverse cultural contexts, with broader implications for public health education in the built environment sector by raising awareness of healthy housing practices, influencing behavior change, and supporting evidence-based interventions at scale. Future studies could incorporate pretest-posttest controlled experiments to investigate its effects on knowledge acquisition and compare it with other conventional education methods.

Further studies could also investigate the long-term impact of behavioral change and implementation of mold prevention practices in real life. Other educational technologies, including the Internet of Things and Augmented Reality/Virtual Reality, or integration of these tools could be explored to provide real-time, interactive information within a physical space, offering a customized learning experience for health-related applications in the built environment. Future research should investigate the game's effectiveness across multiple dimensions, including knowledge acquisition, motivation, system usability, self-efficacy, task load, behavioral change, and long-term knowledge retention.

### Data availability statement

No new data were created or analyzed in this study.

### Acknowledgments

This study received three low-risk notifications (4000028748 for interview, 4000030071 for home visit, and 4000030296 for the main experiment) from the XXX University Human Ethics Committee. In this study, ChatGPT and Grammarly were used solely for proofreading and improving the quality of English language expression. No AI tools were used for drafting, summarizing, or generating the manuscript's scientific content. AI-based text-to-voice generator (i.e. Eleven Labs) and certain graphics created using AI tools were limited to developing the game prototype and did not influence the preparation of the manuscript. The research team extends its heartfelt gratitude to the experts who generously shared their time and valuable insights during the interviews. We also sincerely thank the homeowners who kindly allowed us to visit their residences and capture photographs of mold-prone areas.



This is a common mold picture that can occur in homes

- (1) Which areas in a bedroom are most likely to develop mold? List the specific spots where you believe mold is likely to develop in a bedroom (e.g. bed). You may list more than one spot.  
\_\_\_\_\_
- (2) Which areas in a bathroom are most likely to develop mold? List the specific spots where you believe mold is likely to develop in a bathroom (e.g. mirror). You may list more than one spot.  
\_\_\_\_\_
- (3) Which conditions are necessary for mold growth?  
\_\_\_\_\_
- (4) What temperature range (in °C) is most likely to support mold growth? From \_\_\_ °C to \_\_\_ °C  
\_\_\_\_\_
- (5) What humidity range (in %) is most likely to support mold growth? From \_\_\_ % to \_\_\_ %  
\_\_\_\_\_
- (6) What strategies can you use to prevent mold growth in your home? List the methods you think can work. You may list more than one method.  
\_\_\_\_\_

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