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# Gamification for Wildfire Education and Safety Training: A Systematic Literature Review and Meta-Analysis

Tianqi Huang[1] | Zhenan Feng[1] | Daniel Paes[1] | Fei Ying[1] | Xilei Zhao[2] | Max Kinateder[3] | E. R. (Lisa) Langer[4] | Ruggiero Lovreglio[1]

[1]School of Built Environment, College of Sciences, Massey University, Auckland, New Zealand | [2]Department of Civil and Coastal Engineering, University of Florida, Gainesville, Florida, USA | [3]National Research Council Canada, Ottawa, Ontario, Canada | [4]Scion Group, Bioeconomy Science Institute, Christchurch, New Zealand

**Correspondence:** Tianqi Huang (t.huang1@massey.ac.nz)

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## ABSTRACT

**Background:** Wildfires have become increasingly frequent and destructive, highlighting the need for more effective public education on safety and preparedness. Gamification, the use of game design elements in non-game contexts, offers a promising strategy to enhance learner engagement and educational effectiveness compared to traditional methods.

**Objective:** This study aims to investigate the application of gamification in wildfire education and training, evaluating its effectiveness and highlighting key benefits and challenges.

**Methods:** A systematic literature review was conducted using the PRISMA 2020 framework. The review includes 38 articles selected from the Web of Science (WoS) and Scopus databases, which were published from 2007 to 2025, pertinent to the integration of gamification in wildfire simulation or education applications. This review examined gamification in wildfire education through planning, conducting and reporting stages, and included a meta-analysis to assess the effect size of immersive versus non-immersive applications. Eligible studies were quality assessed using predefined criteria and analysed to extract key characteristics. VOSviewer was used to conduct a keyword co-occurrence analysis, identifying major research themes. SPSS was used to calculate the effect size for the meta-analysis.

**Results and Conclusions:** The findings reveal that different gamification strategies distinctly influence user engagement, motivation, learning effectiveness and overall user experience within wildfire education contexts. Through keyword co-occurrence analysis, the study maps the intellectual landscape of the field, identifying key thematic clusters and emerging trends. Moreover, the meta-analysis provides empirical evidence of the impact of immersive gamification, showing a small but statistically significant effect in learning outcomes (Hedges' $g = 0.18$, $p = 0.04$). This review identifies five critical research gaps: the under-representation of safety behaviour outcomes, limited theoretical integration, lack of community-level and prevention-oriented educational interventions and insufficient attention to implementation barriers. These insights offer a targeted research agenda and practical guidance for advancing the design and deployment of gamified wildfire education initiatives. The novelty and contribution of this study lie in the comprehensive synthesis on the functional roles of gamification in shaping learning outcomes in the wildfire education context.

**Summary**

- What is already known about this topic
  - Wildfires are becoming frequent and severe; increasing the need for wildfire education and safety training.
  - Traditional methods, such as videos and lectures, often lack interactivity and engagement, making it difficult to ensure knowledge retention and behaviour change.
  - Gamification has proven effective in enhancing engagement and motivation in various fields.
  - There is a lack of understanding about how gamification has been applied and tested for wildfire education and safety training.
- What this paper adds
  - Systematically reviews how gamification has been applied in wildfire education and safety training, identifying key technologies and methodologies.
  - Summarises various gamification elements and explains their impacts on education and training.
  - Identifies five critical research gaps and shows a small but statistically significant effect size of immersive gamification on learning outcomes (Hedges' $g = 0.18$, $p = 0.04$).
- Implications for practice and/or policy
  - Gamification can improve wildfire education by making learning more engaging, interactive and effective.
  - Firefighters and policymakers in wildfire-prone areas can benefit from gamified wildfire applications to train safely and enhance emergency response.
  - Governments and educators should consider integrating gamification into wildfire education programmes to improve resilience and risk reduction strategies.

## 1 | Introduction

Wildfires are among the most destructive disasters, causing significant damage to communities and ecosystems every year. In recent years, their increasing frequency and speed have drawn great attention worldwide (Balch et al. 2024; Meng, Huai, et al. 2023). Despite increasing advances in wildfire prediction, monitoring and prevention, climate change is rapidly escalating the frequency and intensity of wildfires (Balch et al. 2024; Bardsley et al. 2018; Jolly et al. 2015). For instance, the Black Summer fires that occurred in Australia in 2019–2020 burned about 19 million hectares of land, destroyed more than 3000 houses and caused at least 33 deaths (Filkov et al. 2020; Haque et al. 2021). The 2018 Camp Fire in the United States led to 85 deaths, destroyed over 18,000 structures, and caused the evacuation of 40,000 people, making it the deadliest and most destructive wildfire in California's history (Maranghides et al. 2023). There is an urgent need to engage the public in learning wildfire safety measures and enhancing wildfire preparedness. Wildfire safety covers a wide range of knowledge domains, such as the spread of wildfires, the use of fire-resistant materials to protect properties, the use of firebreaks to slow down or stop a fire front, and the making and implementation of effective evacuation plans (Penman et al. 2013). The breadth of this knowledge domain poses a significant challenge in engaging and communicating with the public to enhance their preparedness effectively.

There are different ways to disseminate wildfire safety knowledge. Conventional methods include videos, seminars or flyers (Feng et al. 2018; Scorgie et al. 2024). However, these methods may not be effective as they deliver knowledge in a one-way output, lacking interaction with and feedback to learners. In addition, these methods may fail to engage learners and attract their attention. These limitations may hinder the effectiveness of these methods (Gwynne et al. 2019), especially knowledge retention in a long-term period (Scorgie et al. 2024). One possible solution to overcome these limitations is to use gamification to enhance engagement and educational effectiveness.

Gamification is defined as 'the use of game design elements in non-game context' by Deterding et al. (2011). Groh (2012) further explained that gamification is the process of adding game elements (e.g., goals, levels, stories, challenges and competition with other players) to activities that are not related to the game. The aim is to engage participants and increase their motivation and concentration (Alsawaier 2018; Oliveira et al. 2023; Zichermann and Cunningham 2011). Gamification has been used in various fields, such as education, fitness and corporate training. For instance, Duolingo is an application that applies gamification to motivate users and increase their engagement in learning languages. This innovative educational approach can contribute to the effective dissemination and implementation of guidelines on disaster reduction strategies (Feng et al. 2018; Wouters et al. 2013; Zhou et al. 2016).

Gamification could offer potential opportunities to enhance engagement and motivation in wildfire education. However, its effectiveness largely depends on how well it is based on established educational principles. Simply incorporating gamification elements may not be sufficient to guarantee meaningful learning outcomes. Thus, it is necessary to draw upon well-established learning theories. These theories provide the foundational framework for designing gamification applications and gamified experiences (Abd El-Sattar 2023). For instance, cognitive load theory (Sweller 1988) suggests that a good gamification design should avoid information congestion and organise the content hierarchy reasonably. It should guide players to focus on key learning tasks and activate deep processing. Constructivism learning theory focuses on knowledge construction rather than passive knowledge reception (Dalgarno 1996). It suggests that learners actively build their understanding by interacting with new experiences and integrating them with prior knowledge (Jumaat et al. 2017; Newstetter and Svinicki 2015). Gamification can create an immersive and exploratory learning environment for learners. These theories provide conceptual tools for understanding how gamified wildfire education can improve learner engagement, retention and behavioural change. However, there is a lack of understanding of how learning theories have been integrated into game-based wildfire education and training.

Despite some systematic literature reviews (Feng et al. 2018; Kankanamge et al. 2020) investigating game-based education and training for emergencies and disasters (e.g., earthquakes, floods, industrial emergencies, terrorist attacks and indoor fire), there is a lack of understanding about how gamification has been applied and tested for wildfire education and safety training. Wildfire education and safety training is complex and multifaceted, including knowledge of and skills in wildfire propagation, resource allocation, wildfire extinguishment, prevention, evacuation and preparedness strategies (Calkin et al. 2014; Taccaliti et al. 2023). Further, although the existing literature demonstrates the potential of using gamification for educational purposes, it is not clear how gamification can affect and improve wildfire education and safety training (Feng et al. 2018; Lovreglio et al. 2018). Filling these gaps holds both theoretical and practical significance. Theoretically, it contributes to a more comprehensive understanding of how gamification functions within the wildfire education and safety training context. Practically, it provides valuable insights for developing more effective and engaging wildfire education and training programs tailored to real-world needs. To bridge these gaps, this study presents a systematic literature review to examine the applications and effects of gamification on wildfire education and safety training. This study investigates wildfire simulation and display methods, educational purposes, target audience, gamification elements, testing methods and testing results. A synthesis of these findings and the impacts of gamification on wildfire education and safety training is provided.

This paper is organised into several sections. Following the introduction, the background section provides an overview of wildfire education and safety training, and the concept of gamification, highlighting its potential in education and training. The methods section outlines the systematic literature review approach. Next, the results section presents findings related to display methods and platforms, simulation methods, educational purposes, target audiences, gamification elements and test methods and measurements. The discussion section elaborates on the overview of the main findings, identifies research gaps, discusses limitations and suggests future directions. Finally, the conclusion summarises the key insights and implications of the study.

## 2 | Background

### 2.1 | Wildfire Education and Safety Training

Wildfire education programs usually deliver knowledge about wildfire risks and risk reduction measures. These programs play an important role in educating wildfire-prone communities about wildfire behaviours and enhancing their preparedness. The programs, comprised of workshops, seminars and community meetings, have been organised to emphasise the importance of improving community preparedness and cultivating the capacity to respond to wildfire emergencies (Monroe et al. 2013). In Portugal, schools taught wildfire risks and risk reduction measures (Nunes and Martins 2018). The wildfire topics were incorporated into formal geography and natural sciences curricula for the ninth-grade students starting in 2015. Students learned wildfire characteristics, causes, effects and prevention measures. Moreover, a non-formal education and awareness-raising project for the school population, known as the PROSEPE project, was active from its inception in 1993 (Nunes and Martins 2018). This project focused on organising educational activities outside the formal education system, achieving the same aim as the formal wildfire curricula. Restaino et al. (2024) developed a wildfire science curriculum for high school students in the United States, integrating multiple forms of knowledge: technical, cultural, management, institutional and student perspectives. They emphasised that K-12 education can play a critical role in enhancing wildfire preparedness and ecological literacy, while introducing students to career opportunities in fire and ecosystem management.

Wildfires are often accompanied by unpredictable conditions and unprecedented events. This requires innovative techniques to expose these dynamics to learners in education programs. With the frequent use of drones and surveillance cameras, real-life wildfire footage can be captured and presented as video demonstrations (Kankanamge et al. 2022). These virtual demonstrations can be used as video tutorials and shared on social media platforms. They present learners with the dangers and consequences of wildfires by visualising real-life wildfire events. Virtual reality (VR) can convey a realistic visual experience without harming learners. For instance, virtual scenarios were recreated for firefighters to experience dangerous wildfire situations; thus, they could become more confident and prepared when facing the actual events in real life (Haskins et al. 2020). Similarly, VR can immerse learners in a realistic virtual environment, where they can experience wildfire events and learn how to respond to them (Molan et al. 2022b, 2023).

While wildfire education programs aim to achieve different pedagogical outcomes, their effectiveness may vary depending on the forms, media and materials used to deliver the training. The differences may result in different levels of attention, interaction, engagement, knowledge acquisition, knowledge retention, attitude changes and behavioural changes.

### 2.2 | Gamification

Chou (2019) proposed a gamification framework encompassing eight core drives, associated with two types of motivation: extrinsic and intrinsic. These motivation types are defined and explained by the Self-Determination theory by Deci and Ryan (1985, 2000). Extrinsic motivation refers to completing an activity to obtain external rewards (e.g., points and badges). Intrinsic motivation means engaging in an activity for the intrinsic satisfaction it brings (Deci and Ryan 2000).

Gamification transferred teaching and learning materials such as instructions, tasks, feedback, text, video and audio into interactive game elements to increase engagement and motivation (Hamari et al. 2014). It can provide a safe and controlled environment for experiential learning in high-risk environments (De Freitas and Jarvis 2007) and can facilitate collaboration and communication (Bourgonjon et al. 2010). However, gamification also suffers from some limitations, such as the high cost and technical requirements for development (Westera 2019) and the risk that learners may focus more on game elements than educational content (All et al. 2016). Engaging gameplay and essential educational content should be balanced to ensure the effectiveness of education.

Gamification has been used in many fields to improve education and training, such as disaster preparedness, decision-making planning and resource management. There have been several studies showing that gamification has gained public acceptance and has been able to increase awareness of different disasters (Kankanamge et al. 2022; Pereira et al. 2014). Gamification integrated with learning theories can promote children's safety education to address threats such as downed power lines, fires, earthquakes, traffic incidents and dog attacks (Liu et al. 2017). The game ‘Island of Volcanoes’ (Alsaqqaf and Li 2023) uses experiential learning theory to teach volcanic hazards through decision-making and feedback. Novel experiential tools have also been used for wildfire education. Some studies have employed serious games as a form of gamification to teach people how to respond to wildfires, such as evacuation and self-protection measures (Pereira et al. 2014; Sacfung et al. 2014). Gamification adds game elements into non-game contexts to enhance engagement, while serious games are fully developed educational games that provide immersive learning experiences and skill training (Djaouti et al. 2011; Wouters et al. 2009). Compared to traditional teaching and learning methods, both serious games and gamification have shown greater potential to enhance knowledge acquisition, retention and learner engagement by promoting active participation (Papastergiou 2009; Wouters et al. 2013).

Although some studies (Aldunate et al. 2019; Bolijn et al. 2022; Kankanamge et al. 2022; Vega et al. 2017) focus on gamification applications for wildfire education and safety training, a comprehensive understanding of their instructional design, learning targets and effectiveness remains limited.

## 3 | Methods

This study aims to provide a comprehensive understanding of gamification applications in wildfire education and safety training. This study employed a systematic literature review following the five-step method proposed by Khan et al. (2003), including: formulating research questions, identifying relevant literature, assessing the quality of studies, summarising the evidence and interpreting the findings. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework was used to enhance transparency and reproducibility in the literature selection process. Eligible papers were evaluated through a structured quality assessment. Additionally, a keyword co-occurrence analysis using VOSviewer was performed to reveal major thematic clusters and research trends. Last, a meta-analysis was conducted to detect the effect size from the reviewed studies. Findings are reported in Section 4 and discussed in Section 5.

### 3.1 | Formulating Research Questions

This study examines the literature to address seven research questions to achieve the research aim. By answering these questions, this study provides an in-depth understanding of the technologies to visualise wildfires, methods used to simulate wildfires, educational purposes of the applications, the target audience of the applications, gamification elements applied in the applications, testing and evaluation methods and testing and evaluation results. The seven research questions are listed below:

RQ1. *What display methods and platforms have been used to deliver the wildfire simulation and education applications?*

RQ2. *What simulation methods have been used to simulate wildfires in these applications?*

RQ3. *What are the educational purposes of these applications?*

RQ4. *Who are the target audiences of these applications?*

RQ5. *What gamification elements have been applied in these applications?*

RQ6. *What are the methods to test and evaluate these applications?*

RQ7. *What are the findings after testing and evaluating these applications?*

This study aims to explore the integration of gamification in wildfire simulation or education applications and its effectiveness. Display methods and platforms are the foundations to deliver these applications (RQ1), as they provide the means for user interaction and accessibility. Simulation is employed to simulate and visualise wildfire dynamics in these applications (RQ2), which form the core technical aspect ensuring the authentic and accurate presentation of wildfires. Based on this, the educational purposes of these applications are introduced (RQ3), as the purposes can directly shape the design and functionalities of the applications. Understanding target audiences (RQ4) is essential for educational purposes, as they influence both the educational objectives and gamification strategies. Building upon these fundamental concepts, this study identifies gamification elements (RQ5) to inform the means and effects of applying them in gamification applications. Then, the methods used to test and evaluate the applications (RQ6) are discussed to ensure the rigour and validity of the findings. Finally, testing and evaluation (RQ7) findings are presented, providing a comprehensive understanding of the effectiveness of gamification in wildfire education and safety training.

### 3.2 | Identifying the Relevant Work

This review followed the PRISMA 2020 framework to identify eligible articles for the review (Page et al. 2021). Figure 1 illustrates the filtering process using the PRISMA workflow. First, Scopus and Web of Science (WoS) were used as the databases to retrieve relevant work. Scopus claims to be the largest abstract and citation database of research literature (Bar-Ilan 2008), and WoS is another major database that provides access to peer-reviewed literature across the fields of science and engineering (Wuchty et al. 2007). The keyword strings used for searching the literature were as follows: ‘wildfire’ OR ‘bushfire’ OR ‘forest fire’ AND gam* OR ‘virtual reality’ OR vr OR ‘augmented reality’ OR ar.

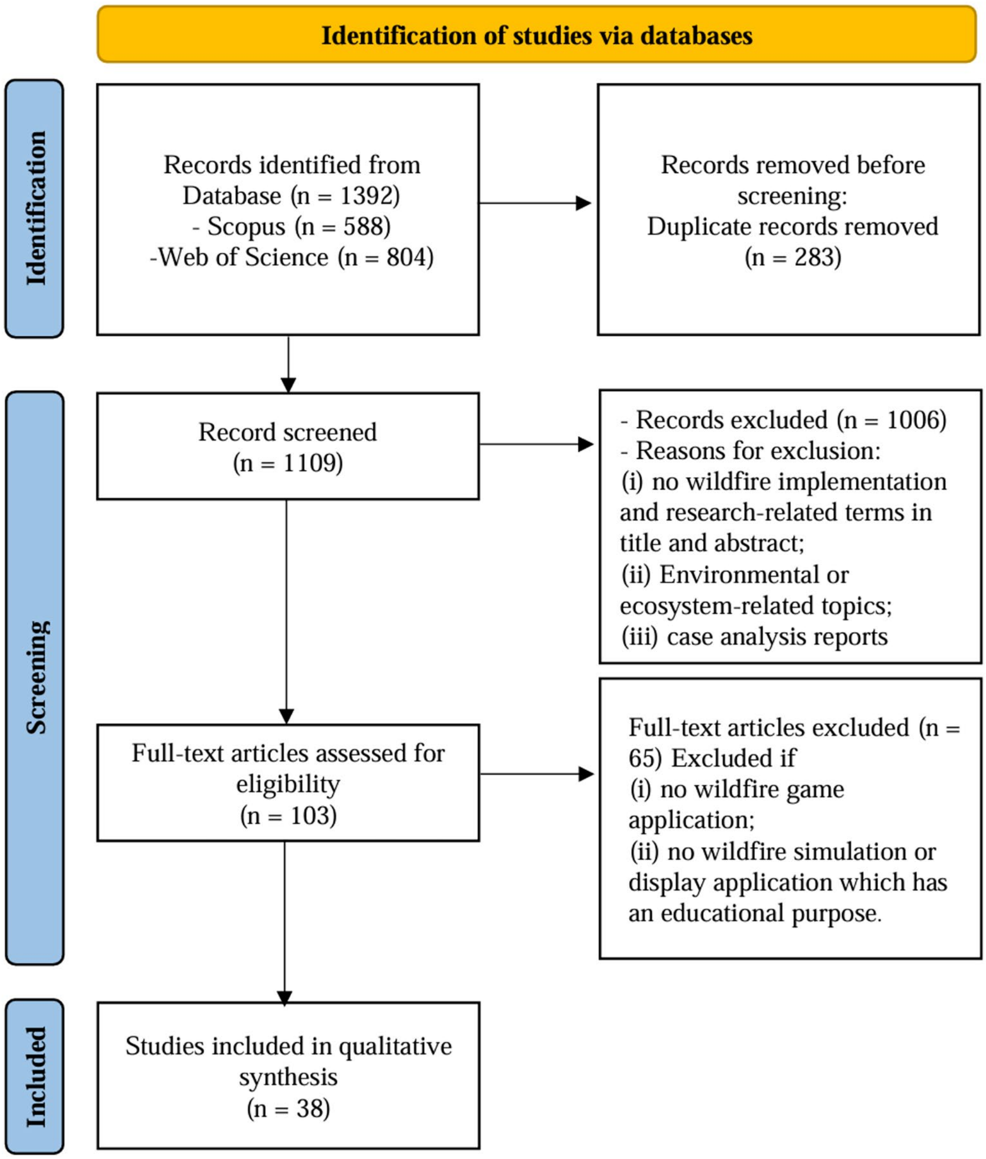


**FIGURE 1** | The literature selection process derived from the PRISMA framework.

The string included two parts, where the first part covered various terminologies for wildfires, and the second part included different forms of gamification and gamified applications. There were no other restrictions on retrieving papers, such as time span or language. A total of 1392 results were retrieved from two databases: 588 from Scopus, which was searched in May 2024, and 804 from WoS, searched in April 2025. Upon organising the identified results by titles, 283 duplicates were found. After removing the duplicates, an initial screen was conducted by scanning the titles and abstracts of the search results. Papers were excluded if they met one of the following criteria:

i. There was no wildfire-related research in the paper; or
ii. The paper focused on environmental or ecosystem-related issues (e.g., wildfire pollution or the impacts on the ecology of plants and animals); or
iii. The paper presented case analysis reports of wildfires that occurred in the past.

After this initial screening, 103 papers remained. Then, full-text reading was conducted to assess the eligibility. The papers were excluded if they met one of the following criteria:

i. The paper does not introduce or describe a gamification application targeting wildfire education; or
ii. The paper does not introduce or describe a wildfire simulation or visualisation application that is applied for education.

After this final filtering process, 38 papers remained as eligible articles for this review (Aldunate et al. 2019; Bolijn et al. 2022; Castrillón et al. 2011; Clifford et al. 2018; Cobian et al. 2018; Ghosh et al. 2024; Heyao and Tetsuro 2022; Hoang et al. 2008,

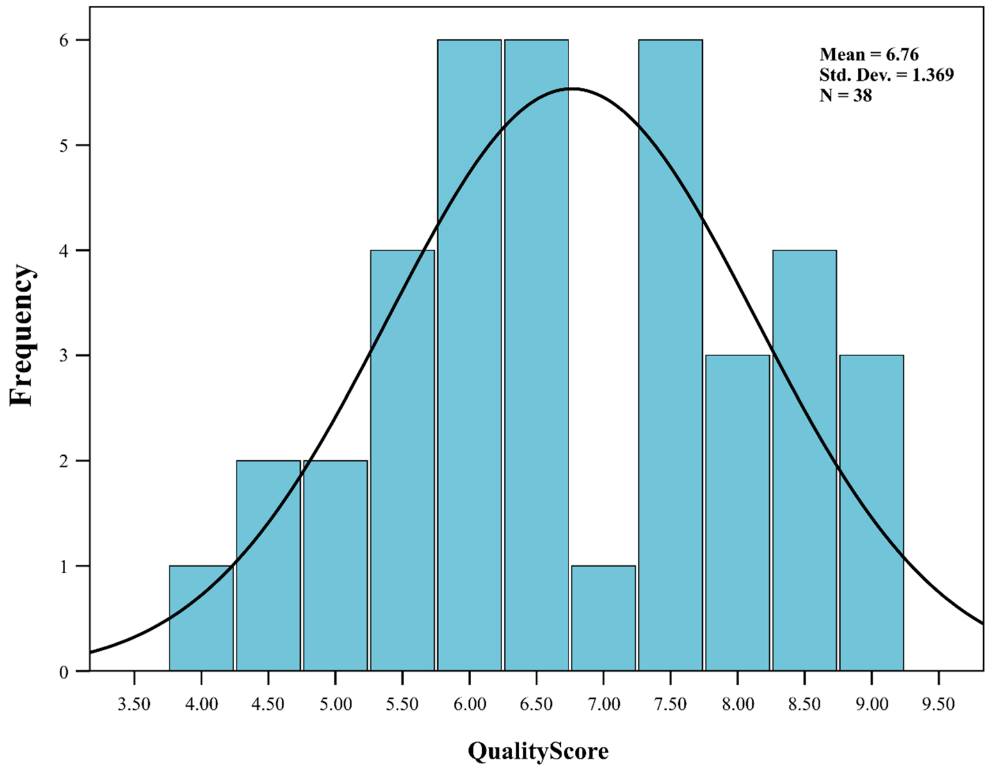


**FIGURE 2** | Quality scores for eligible papers.

2010; Howe et al. 2018; Huang et al. 2012; Ji et al. 2024; Johns et al. 2024; Kankanamge et al. 2022; Kazanidis et al. 2018; Lewis et al. 2020; Lino et al. 2021; Meijers et al. 2023; Meng, Lu, et al. 2023; Molan and Weber 2021; Molan et al. 2022a, 2022b, 2023; Moreno et al. 2014; Pereira et al. 2014; Rui et al. 2016; Sahli and Moulin 2009; Schmidt et al. 2008; Sermet and Demir 2022; Sherman et al. 2007; Smith et al. 2016; Taylor et al. 2025; Vega et al. 2017; Vigna et al. 2024; Wahlqvist et al. 2021; Wu et al. 2023; You et al. 2022; Yun et al. 2011).

### 3.3 | Quality Assessment

After identifying the eligible papers, a quality assessment was conducted to evaluate the reliability and relevance of the eligible articles to the focus of this review. Each paper was independently reviewed and rated by two researchers based on the following three criteria:

i. How appropriate and relevant is the prototype design in addressing the core questions posed in this review?
ii. To what extent are the methods and analyses suitable for addressing the research questions posed in this review?
iii. To what extent is the study's focus aligned with the research questions of this review?

Each criterion was rated on a scale from 1 to 3, with 1 indicating *low relevance* and 3 indicating *high relevance*. The total score for each paper was calculated by summing the scores. The final score for each paper was determined by averaging the two researchers' scores. As a result, the final possible scores ranged from 3 to 9, with higher scores indicating higher relevance.

Figure 2 presents a histogram illustrating the scores of the papers. The mean score was 6.76 with a standard deviation of 1.369. Most papers received moderate to high quality scores around the 6–8.50 range. Only a small number of studies scored at the lower end (i.e., 4–4.50), indicating limited relevance or methodological rigour. This distribution suggests that most of the included studies were sufficient to meaningfully contribute to the synthesis and analysis in this review. Given that the total number of eligible articles is not large, this review analysed all articles to answer the seven research questions.

### 3.4 | Data Collection and Analysis

The included studies were organised using EndNote to enable efficient reference management. Data from the 38 eligible articles were systematically coded to address the seven research questions, focusing on: (1) display methods and platforms; (2) simulation techniques; (3) educational purposes; (4) target audiences; (5) gamification elements; (6) testing methods and measurements; and (7) findings from testing and evaluation. Coding was conducted using Microsoft Excel, allowing for a structured process and meaningful cross-study comparisons. To ensure reliability, two independent authors verified the coding. Additionally, VOSviewer was employed to perform keyword co-occurrence analysis, identifying major research trends and visualising thematic clusters. For the meta-analysis, studies reporting comparative learning outcomes,

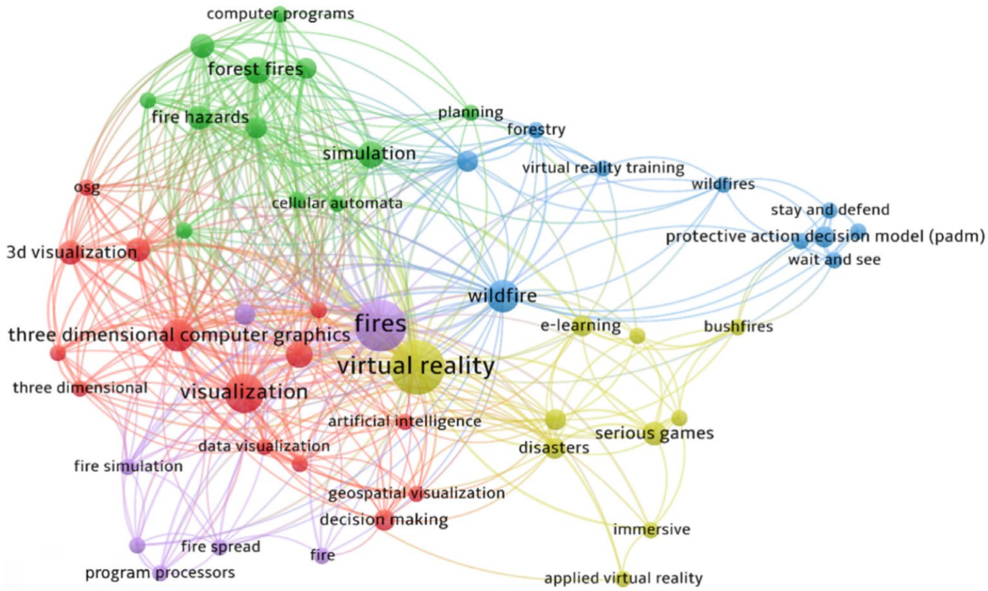


**FIGURE 3** | Thematic clusters identified through keyword co-occurrence analysis.

including sample size, mean and standard deviation, were identified. SPSS was used to compute effect sizes and conduct the meta-analysis.

Next, the eligible papers were coded and analysed to provide direct answers to the seven research questions. The findings are reported in the following sections.

## 4 | Results

The 38 eligible articles were published between 2007 and 2025 (Figure 4). A clear growth trajectory in the number of studies over the past two decades can be observed, with rapid acceleration beginning around 2018 and peaking in 2022. The recent dip in 2025 may reflect incomplete data collection rather than a true decline.

To identify the main themes and relationships across the eligible articles, a keyword co-occurrence analysis was conducted using VOSviewer. A total of 377 keywords were extracted from the papers. To enhance clarity and relevance, only keywords appearing at least two times (53 keywords) were selected for visualisation in the keyword map (Figure 3).

The keyword map revealed several thematic clusters. The red cluster focused on visualisation and simulation technologies, with terms such as three-dimensional computer graphics, visualisation and geospatial visualisation. The green cluster related to wildfire modelling and hazards, including terms like forest fires, fire hazards and simulation. Additionally, the blue cluster contained terms such as protective action decision model (PADM), stay and defend, and wait and see to highlight decision-making and behaviour responses during wildfire emergencies. Keywords such as serious games, e-learning and disasters formed a yellow cluster around gamified learning and education. The purple cluster included program processors, fire simulation and fire spread, pointing to technical optimisation and system architecture. The central terms VR, fires and wildfire linked across these clusters, highlighting the interdisciplinary nature of wildfire education research.

## 4.1 | Display Methods and Platforms

### 4.1.1 | Display Methods

The analysis of the selected studies found three popular display methods to present wildfire applications, including VR, 2D or 3D animations and augmented reality (AR) (Figure 4a). VR and 2D or 3D animations were found to be the most popular methods of presenting wildfires. VR included immersive environments, where virtual experiences were delivered via head-mounted displays (HMDs) or projection-based systems. Non-immersive virtual environments, typically accessed through personal computers (PCs), were classified under 3D animations. These findings reflect the range of display methods employed in the studies reviewed.

In recent years, VR has gained more attention for wildfire applications. For instance, Meijers et al. (2023) used an HMD to show a 360° video of an actual forest fire that happened in the United States. Molan et al. (2022b) created immersive virtual environments to investigate the behaviours and intentions of people when a wildfire occurred (Molan and Weber 2021; Molan et al. 2023). You et al. (2022) presented a 3D animation of wildfire spread by using the finite state machine (FSM). Rui et al. (2016) presented fire propagation on a 2D map using the algorithms which determine wildfire intensity, direction and duration, while taking into account the effects of slope, wind direction and vegetation type on the wildfire's behaviour. Furthermore, Kazanidis et al. (2018) used AR to create an interactive and immersive learning experience for students and educated them about natural disasters, providing various educational content in the forms of text, images, animations, videos and comics.

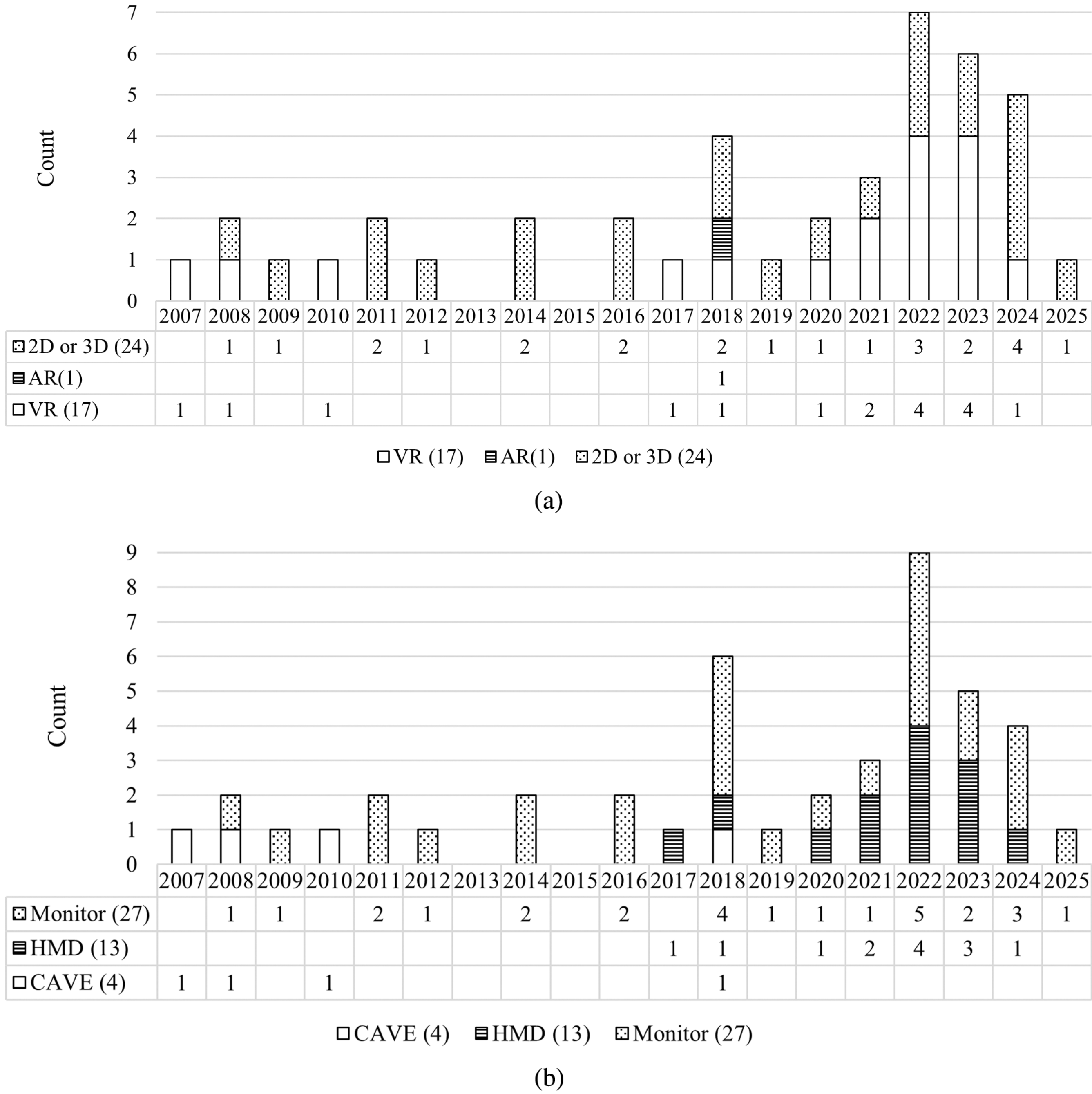


**FIGURE 4** | Frequency of publications over time separated by display methods (a) and platforms (b).

#### 4.1.2 | Display Platforms

Different display methods may require varied platforms to display wildfire applications. Various display platforms were found in this study, including monitors, cave automatic virtual environment (CAVE) and HMDs as illustrated in Figure 4b. Prior to 2022, monitors were the dominant platform for visualising wildfires. The use of HMDs has grown substantially since 2017. Monitors are the most common platforms for presenting wildfires, as many 2D or 3D animations rely on wildfire simulators to model fire behaviour and particle systems to render visual effects like smoke and flames (Castrillón et al. 2011; Huang et al. 2012; Yun et al. 2011). Prior to 2010, several studies presented wildfire in the form of VR using CAVE (Hoang et al. 2008, 2010; Sherman et al. 2007).

With technological advancement and the release of commercial immersive VR hardware in 2016, some studies have started to employ HMDs such as HTC Vive and Oculus Rift to provide immersive VR experiences. For instance, Vega et al. (2017) built a virtual environment with HTC Vive and educated learners on how to safely build and maintain a campfire to prevent wildfire. Monitors, such as those on televisions, PCs, smartphones and tablets, have consistently been widely utilised in research. Clifford et al. (2018) employed three systems to provide aerial firefighting training. Alongside the use of VR headsets and a three-wall CAVE-like projection system, they integrated high-definition televisions (HDTVs) to provide an approximate 54° field of view to simulate the view of the area outside the fire helicopter cockpit. Participants sat 1 m from the television and

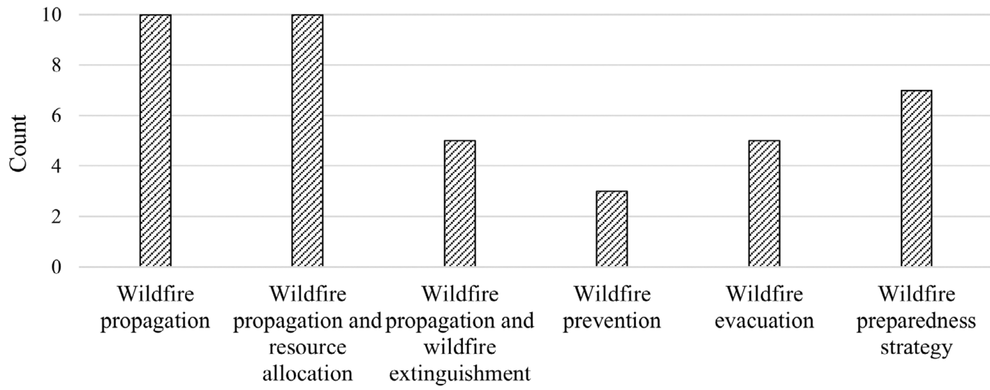


**FIGURE 5** | Educational purposes.

utilised a mouse to scan the outside area to complete the assigned task. Moreover, web-based applications have also played an important role in wildfire applications. For instance, Stop Disasters! can create a wildfire scenario and teach people about hazard prevention, which is available as a web-based application (Kankanamge et al. 2022; Pereira et al. 2014). One advantage of web-based applications is accessibility, where different devices (e.g., PCs, tablets and smartphones) can run the applications.

## 4.2 | Simulation Methods

Popular wildfire simulation methods include vector-based and raster-based simulations. Vector-based simulations can simulate wildfire spread in more detail by accounting for key factors influencing fire behaviour, such as wind speed and direction, topography and vegetation type (Hoang et al. 2010). Raster-based simulations implement the spread of wildfires using discrete methods such as cellular automata (CA) (Hoang et al. 2010; Wolfram 1983). Fifteen studies employed a vector-based simulator called the FARSITE fire simulator, which integrated Rothermel's surface fire spread model and OpenSceneGraph (OSG) for terrain construction (Castrillón et al. 2011; Huang et al. 2012; Yun et al. 2011). The wildfire simulated by this simulator was dynamically presented by combining topographic, fuel and wind conditions for learners to plan for fire behaviour across complex landscapes. Rui et al. (2016) simplified Rothermel's model and developed a real-time web-based wildfire simulation system (RWWSS) for wider utilisation. Four studies reported the use of raster-based simulations. Aldunate et al. (2019) and Meng, Lu, et al. (2023) used meta-CA as a central element of wildfire simulation models in their studies. CA and their improved models are commonly used for simulating wildfire spread, whereas FSMs are rarely applied in wildfire research. You et al. (2022) created an FSM-based tree pyrolysis model to simulate tree combustion from heating to pyrolysis and finally to carbonisation. In addition to these two simulation methods, several studies used game engines (e.g., Unity) and their embedded visual and particle systems to simulate wildfires by qualitative methods (Howe et al. 2018; Kazanidis et al. 2018; Vega et al. 2017), and some studies used video footage to demonstrate historically documented wildfires (Meijers et al. 2023). In this case, the wildfires were not simulated following fire models and fire dynamics. This study found that existing wildfire applications have paid a lot of attention to simulating and visualising realistic fire spreads and behaviours, which may bring a sense of immersion and urgency and benefit educational outcomes.

## 4.3 | Educational Purposes

The primary educational purposes of the wildfire applications include teaching learners about wildfire propagation ($n=10$), wildfire propagation and resource allocation ($n=10$), wildfire propagation and wildfire extinguishment ($n=5$), wildfire prevention ($n=3$), wildfire evacuation ($n=5$) and wildfire preparedness strategies ($n=7$) (Figure 5).

Ten studies were targeted at demonstrating wildfire propagation. These studies employed different wildfire simulation methods and display technologies to present how wildfires spread. Some studies ($n=10$) have highlighted the importance of resource management while demonstrating the spread of wildfires (Aldunate et al. 2019; Lewis et al. 2020; Schmidt et al. 2008). These studies set up scenarios for fire managers and crisis management professionals to exercise resource allocation practices and decision-making processes.

Five studies targeted firefighting skills as the educational purpose of extinguishing a wildfire, while demonstrating wildfire propagation provided realistic and interactive environments for the training of using extinguishers and spray guns to put out wildfires. Meng, Lu, et al. (2023) used interactive methods within a virtual 3D environment to teach learners the process of extinguishing wildfires. The simulation allowed learners to experience different strategies for extinguishing wildfires, such as water guns, helicopter-delivered water and rainfall.

For wildfire prevention ($n=3$), Vega et al. (2017) created an immersive environment to educate learners on how to set a campfire safely to prevent wildfires. Bolijn et al. (2022) designed a serious game called Benni's Forest to teach fire prevention strategies in forests, such as creating a fire break and planting fire-resistant trees.

Five papers focused on wildfire evacuation. Wahlqvist et al. (2021) used the WUI-NITY (wildland–urban interface built using a popular game development engine) platform to help teach learners about wildfire evacuation by simulating dynamic conditions of both wildfires and human behaviour during evacuations. Molan et al. (2022b) employed VR to immerse learners in simulated wildfire scenarios, aiming to shift their decision-making process towards early evacuation and increased preparedness (Molan and Weber 2021; Molan et al. 2023).

Additionally, seven studies educated learners about wildfire preparedness strategies. For instance, 'Stop Disasters!' teaches learners about relocating victims and communities to receive medical care and education, upgrading houses with fire-resistant materials, setting firebreaks and defences, providing training in the community and setting up evacuation signs (Kankanamge et al. 2022; Pereira et al. 2014).

These studies provide a variety of educational purposes from the wildfire applications; however, most of them target wildfire spread and propagation, and little attention has been paid to response measures for the public.

### 4.4 | Target Audiences

Section 4.3 outlined various educational purposes covered by the wildfire applications. Accordingly, these applications have different targeted audiences, including professionals ($n=20$), policymakers ($n=9$), students and educators ($n=5$), the public and communities ($n=18$) and academic researchers ($n=5$) (Figure 6).

Professionals ($n=20$) included practitioners working in wildfire response and emergency services, such as firefighters and forest service personnel. These professionals can benefit from the wildfire applications by learning how to properly respond through realistic simulations of wildfire scenarios, as well as training on various wildfire extinguishing strategies. For instance, Heyao and Tetsuro (2022) applied a VR training system to train firefighters how to use fire hoses to put out wildfires in a virtual environment. Similarly, Clifford et al. (2018) developed a multi-sensory VR training simulator for airborne firefighters to exercise their skills in aerial wildfire suppression and improve situation awareness during Air Attack Supervision (AAS).

Policymakers ($n=9$) included decision-makers and government officials who are responsible for formulating policies and making decisions when disasters strike. For instance, Aldunate et al. (2019) developed a web-based game platform for disaster management agencies, which can simulate wildfire and emergency situations to let them practise decision-making processes and improve their management skills.

Five applications have been used for elementary and middle schools as a novel method for educating students about wildfire knowledge and providing them with new perspectives about wildfires. For example, Cobian et al. (2018) used an interactive web-based game called GridFire to deliver knowledge about wildfire propagation to elementary school students.

Various applications were available on computers and mobile devices as they targeted the public and communities ($n=18$). For instance, Pereira et al. (2014) introduced a web-based serious game called 'Stop Disasters!', which could be easily accessed by different devices and help learners understand the risks of wildfires and risk mitigation measures. Rui et al. (2016) developed the RWWSS to educate the public on wildfire risks and prevention through interactive simulations. Particularly, among these 18 studies, 2 of them placed a significant emphasis on community-level engagement. For instance, Wahlqvist et al. (2021) introduced WUI-NITY, a Unity3D-based platform that simulated wildfire spread and evacuation in wildland–urban interface (WUI) communities. It integrated fire, pedestrian and traffic models to enhance community preparedness, improve situational awareness and support emergency planning and response. It is important for the public and communities to improve their awareness of wildfire hazards and practice the response measures they should take when a wildfire occurs.

Five studies, while demonstrating their educational purposes, also offered new directions and theoretical foundations for researchers interested in the field of disasters, wildfires and emergency response. For example, You et al. (2022) applied an FSM to simulate the process of tree combustion with the details of pyrolysis and carbonisation, and based on this, they proposed a novel approach to model and simulate wildfires, providing a reliable visualisation framework for future wildfire research.

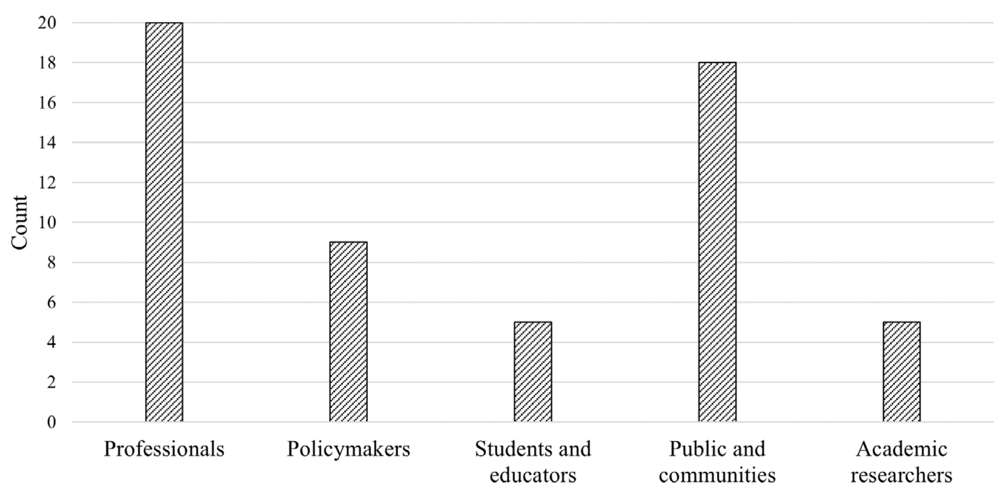


**FIGURE 6** | Target audiences.

### 4.5 | Gamification Elements

Gamification elements can be used to increase engagement, motivation and participation and help learners achieve their goals efficiently. Twenty studies explicitly explained the gamification elements they applied to their wildfire applications (Aldunate et al. 2019; Bolijn et al. 2022; Cobian et al. 2018; Ghosh et al. 2024; Heyao and Tetsuro 2022; Howe et al. 2018; Ji et al. 2024; Johns et al. 2024; Kankanamge et al. 2022; Kazanidis et al. 2018; Lewis et al. 2020; Lino et al. 2021; Molan and Weber 2021; Molan et al. 2022a, 2022b, 2023; Pereira et al. 2014; Sermet and Demir 2022; Vega et al. 2017; Vigna et al. 2024). Another 15 studies did not specify gamification elements; however, the elements could be observed through their applications and papers (Castrillón et al. 2011; Clifford et al. 2018; Hoang et al. 2008, 2010; Huang et al. 2012; Meng, Lu, et al. 2023; Moreno et al. 2014; Rui et al. 2016; Sahli and Moulin 2009; Sherman et al. 2007; Taylor et al. 2025; Wahlqvist et al. 2021; Wu et al. 2023; You et al. 2022; Yun et al. 2011) (Table 1). Finally, three studies demonstrated their educational purposes, but no gamification elements could be identified. Table 1 summarises the names and definitions of gamification elements.

#### 4.5.1 | Game Dynamics

Several studies explored game dynamics inspired by existing game genres, such as role-playing games (RPG) and real-time strategy (RTS), to shape their applications. Based on the gameplay of RPG, Bolijn et al. (2022) designed a game called Benni's Forest, allowing learners to play the role of a forest manager to manage forest resources. Learners could make strategic decisions, such as determining the types of trees to plant and creating fire breaks to prevent wildfires. Aldunate et al. (2019) proposed a role-playing video game to help learners improve decision-making skills. The game allowed learners to act in different roles, including experts and trainees. Training providers can customise the difficulty of the simulation, as well as the scenarios, according to the level and skill needs of the trainee. In this way, both novice and experienced learners can practise decision-making in increasingly complex and realistic conditions. Moreover, Lino et al. (2021) applied RTS elements in their application, allowing learners to command-and-control vehicles that could move to assigned positions, follow roads, and react to terrain changes. This feature enables learners to simulate the strategic deployment of resources, such as fire trucks, which is critical for managing wildfires effectively. Learners could practise their decision-making skills on resource allocation to plan against a wildfire situation.

In addition to genre-inspired approaches, some studies employed other game dynamics to enhance their wildfire applications. Cobian et al. (2018) developed a tool called GridFire that incorporated stochastic gameplay. This could help simulate the unpredictability of wildfire propagation, providing learners with a sense of the stochastic nature of fire behaviour and increasing the replay value of the game. Howe et al. (2018) have added a virtual currency and cost system to their application for simulating real-world trade-offs and decision-making processes. Learners had to carefully plan their actions as they came up with different costs. Vega et al. (2017) offered delayed feedback where learners could make mistakes and fail a mission during the game and receive feedback at the end. In this way, learners could obtain a better sense of immersion and user experience without getting interrupted during the gameplay. Kazanidis et al. (2018) used comics and visual storytelling to create a storyline and make disaster knowledge more understandable and appealing, thus better engaging learners and delivering knowledge.

#### 4.5.2 | Gamification Mechanics

Some studies emphasised the integration of gamification mechanics such as goals, challenges, real-time feedback, scores, achievements and rewards, to enhance engagement and learning outcomes within their applications. For instance, Molan et al. (2022b) set up several interactive decision points. They also incorporated environmental triggers to prompt user decisions. These elements provided clues to help learners recognise the need for rapid, logical decision-making in the face of wildfire. The application also included interactive actions, such as upgrading houses and replacing building materials. Learners could receive real-time feedback based on these interactive actions and evaluate their decisions. Challenges and goals were also set for learners, such as preventing casualties and protecting properties, providing a sense of urgency and time pressure to learners. At last, learners were allowed to review scenarios and knowledge items at the end of the application, enhancing their understanding and knowledge gain (Molan and Weber 2021; Molan et al. 2023).

Kankanamge et al. (2022) and Pereira et al. (2014) employed an application named 'Stop Disaster!', which was gamified with various game mechanics, including goals, challenges, role-playing, difficulty levels, scores, real-time feedback and unlockable content. Learners obtained clear goals to protect human lives and faced unique challenges to overcome to achieve the goals. They acted as a fire warden to make critical decisions and take actions to safeguard facilities and halt the spread of wildfires. To accommodate varying skill levels, the application offered difficulty settings to ensure challenges were neither too easy nor too difficult, facilitating a flow state for learners. A scoring system was in place to motivate learners, while real-time visual feedback provided immediate insights into the consequences of learners' decisions and actions. For instance, if learners failed to clear flammable materials on time, wildfires would spread and threaten facilities and human lives. Learners could unlock key facts and messages when they achieved certain milestones or completed specific tasks. In the web-based game developed by Cobian et al. (2018), goals were set for learners, and a badge system was in place to reward them if they accomplished the goals. In this case, extrinsic motivation started to play a role in motivating learners.

For the studies that did not discuss gamification elements explicitly, they primarily employed user interaction, user control and real-time feedback to facilitate the delivery of education. These applications allowed learners to interact with visual content. They could use progress bars and other user interface elements

**TABLE 1** | Gamification elements.

| Gamification elements | Definitions | References |
|---|---|---|
| User Interaction and control | Enables user autonomy and engagement through interaction, like progress bars and scene customisation. | Sherman et al. (2007), Hoang et al. (2008), Hoang et al. (2010), Castrillón et al. (2011) Huang et al. (2012), Yun et al. (2011), Cobian et al. (2018), Lewis et al. (2020), Wu et al. (2023) Aldunate et al. (2019) Rui et al. (2016), Sermet and Demir (2022), Lino et al. (2021), You et al. (2022), Ghosh et al. (2024), Taylor et al. (2025), Vigna et al. (2024) |
| Replayability | Encourages repeated participation for long-term engagement. | Cobian et al. (2018), Heyao and Tetsuro (2022), Ji et al. (2024), Johns et al. (2024) |
| Real-time feedback | Provides immediate responses to guide user actions. | Sherman et al. (2007), Hoang et al. (2008), Hoang et al. (2010), Castrillón et al. (2011), Yun et al. (2011), Huang et al. (2012), Moreno et al. (2014), Cobian et al. (2018), Wahlqvist et al. (2021), Lewis et al. (2020), Wu et al. (2023), Aldunate et al. (2019), Meng, Lu, et al. (2023), Rui et al. (2016), Heyao and Tetsuro (2022), Sermet and Demir (2022), Lino et al. (2021), Sahli and Moulin (2009), Molan and Weber (2021), Molan et al. (2022b) Molan et al. (2023), Pereira et al. (2014), Kankanamge et al. (2022), Howe et al. (2018) Vega et al. (2017), Bolijn et al. (2022), Kazanidis et al. (2018) You et al. (2022), Clifford et al. (2018), Molan et al. (2022a), Ghosh et al. (2024), Ji et al. (2024), Johns et al. (2024), Taylor et al. (2025), Vigna et al. (2024) |
| RTS | A game genre requiring real-time tactical decisions. | Lino et al. (2021) |
| Role-playing | Players assume characters to enhance immersion. | Sherman et al. (2007), Hoang et al. (2008), Hoang et al. (2010), Huang et al. (2012), Lewis et al. (2020), Aldunate et al. (2019), Heyao and Tetsuro (2022), Sermet and Demir (2022), Sahli and Moulin (2009), Pereira et al. (2014), Kankanamge et al. (2022), Bolijn et al. (2022), Kazanidis et al. (2018), Clifford et al. (2018), Molan et al. (2022a), Ghosh et al. (2024), Johns et al. (2024), Vigna et al. (2024) |
| Challenges and goals | Clear objectives that drive motivation and progress. | Sherman et al. (2007), Castrillón et al. (2011), Moreno et al. (2014), Cobian et al. (2018), Aldunate et al. (2019), Rui et al. (2016), Lino et al. (2021), Sahli and Moulin (2009), Molan and Weber (2021), Molan et al. (2022b), Molan et al. (2023), Pereira et al. (2014), Kankanamge et al. (2022), Howe et al. (2018), Vega et al. (2017), Bolijn et al. (2022), Kazanidis et al. (2018), Clifford et al. (2018), Molan et al. (2022a), Ji et al. (2024), Johns et al. (2024) |
| Scores and achievements | Rewards users with points, badges or milestones. | Cobian et al. (2018), Aldunate et al. (2019), Molan and Weber (2021), Pereira et al. (2014), Kankanamge et al. (2022), Howe et al. (2018), Vega et al. (2017), Bolijn et al. (2022), Molan et al. (2022a) |
| Comics and visual storytelling | Uses visuals to enhance engagement and communication. | Kazanidis et al. (2018), Johns et al. (2024) |

(Continues)

**TABLE 1** | (Continued)

| Gamification elements | Definitions | References |
|---|---|---|
| Varying difficulty | Adapts challenges to different skill levels. | Heyao and Tetsuro (2022), Molan et al. (2022b), Molan et al. (2023), Pereira et al. (2014), Kankanamge et al. (2022), Molan et al. (2022a), Ji et al. (2024) |
| Leaderboards | Ranks users to encourage competition. | Pereira et al. (2014), Kankanamge et al. (2022) |
| Virtual currency and costs | In-game currency for transactions and engagement. | Howe et al. (2018) |

to control on-screen content, receiving real-time feedback. For instance, Castrillón et al. (2011) provided a 3D interactive interface for learners to input parameters such as weather conditions and ignition points to customise a simulation. Learners could also interact with and manage resources like vehicles, and the system allowed learners to view real-time dynamics of wildfire spread and resource locations. In addition to enabling learners to customise simulation scenarios and manage objects within the scene, Yun et al. (2011) developed a slider that allowed learners to control the simulation time of wildfire propagation. Learners can observe and review the wildfire spread dynamically.

Figure 7 summarises the major gamification elements integrated into wildfire applications for education and training, showing the number of gamification elements used to facilitate each educational purpose. According to the figure, most wildfire applications employed real-time feedback. The diagram summarises the gamification elements in various aspects of wildfire research, providing a valuable reference for the selection of gamification elements in future wildfire gamification studies.

### 4.6 | Testing Methods and Measurements

More than half of the studies ($n=23$) presented the testing of their wildfire applications. In general, these studies measured the performance of fire spread algorithms, knowledge acquisition and retention, user experience, behavioural intentions, sense of presence and risk perceptions. The main methods to test these measurements include algorithm analysis and performance comparisons ($n=2$), questionnaires ($n=19$), qualitative feedback ($n=8$), physiological measurements ($n=1$) and case studies ($n=3$) (Figure 8).

The performance of the fire spread algorithms for wildfire simulation was examined through algorithm analysis and performance comparisons, supplemented by expert validation and real-time performance and scalability testing (Moreno et al. 2014; You et al. 2022).

For user evaluation, questionnaires ($n=19$) were the common measurement tools used to test the applications. Data on knowledge acquisition were generally collected by pre-test and post-test questionnaires or embedded questions in the applications. Follow-up questionnaires were used to measure knowledge retention in the long term. For instance, Molan et al. (2022b) conducted a knowledge retention test 3 months after exposing learners to their wildfire application (Molan et al. 2023). Several studies employed validated questionnaires to assess user experience and sense of presence. For instance, Pereira et al. (2014) used the Intrinsic Motivation Inventory (IMI) questionnaire to assess learners' subjective game experience related to motivational dimensions, including enjoyment and perceived value. Heyao and Tetsuro (2022) and Clifford et al. (2018) adopted the Igroup Presence Questionnaire (IPQ) to assess learners' sense of being in the virtual environment. Clifford et al. (2018) employed the Simulator Sickness Questionnaire (SSQ) to evaluate learners' motion sickness during the virtual experience.

Eight studies invited learners to give qualitative feedback on the game design and experience. For instance, Pereira et al. (2014) asked learners to express their comments after experiencing the game. They obtained positive comments regarding the game concept and enjoyment, and negative comments about the limitations of the game interface and interaction. Kankanamge et al. (2022) used word trees, sentiment analysis and attitude analysis derived from social media analysis to explore public perceptions and emotions regarding traditional and novel approaches to wildfire education.

In addition to questionnaires and qualitative comments, physiological measurement ($n=1$) was another way to evaluate the applications. Heyao and Tetsuro (2022) used electrocardiogram (ECG) devices to measure heart rate variability (HRV) and functional infrared thermal imaging to measure emotional responses based on facial temperature.

Finally, three studies employed case studies to test their applications. Sermet and Demir (2022) tested the GeospatialVR framework through various case studies, one of which was a simulation of a wildfire scenario. The framework simulated wildfire propagation by utilising real-time data from thermal detectors and air pollution sensors. It tested how the virtual environment could provide visualisations of wildfire propagation, wind, terrain and other factors. This case evaluated how the system could support decision-making during wildfires by focusing on the accuracy of visualising fire location, progression and environmental factors such as wind speed and vegetation. Kankanamge et al. (2022) selected the Australian bushfires of 2019–2020 as the case study and the background to test the effectiveness of the gamified disaster education approach. They used this case to evaluate how the public felt about traditional disaster education methods and identify the demand for new approaches such as gamified education. Then they employed 'STOP Disasters!' to educate learners about wildfire and preparedness strategies.

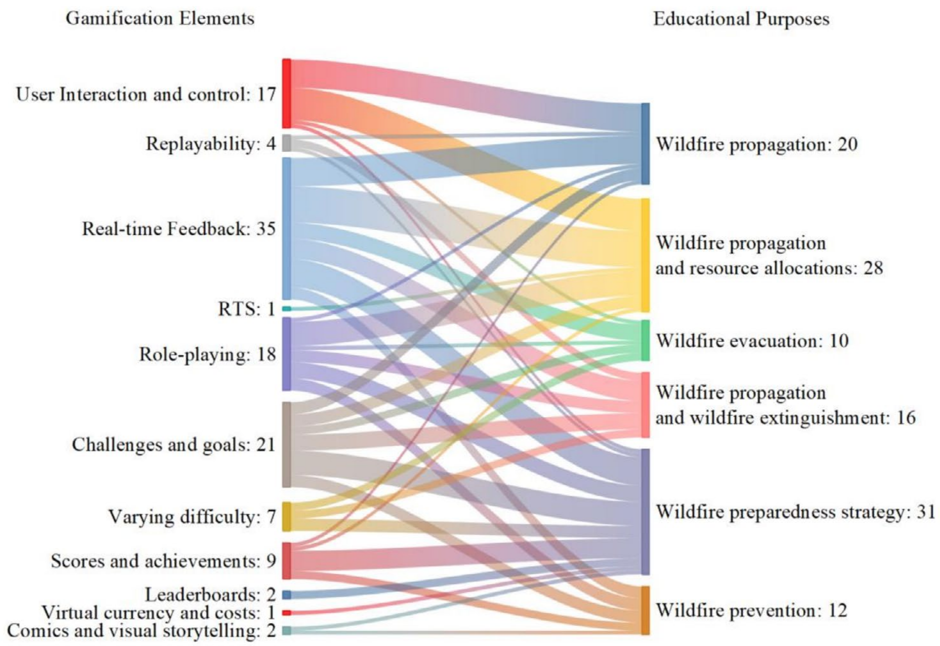


**FIGURE 7** | The relationship between gamification elements and educational purposes.

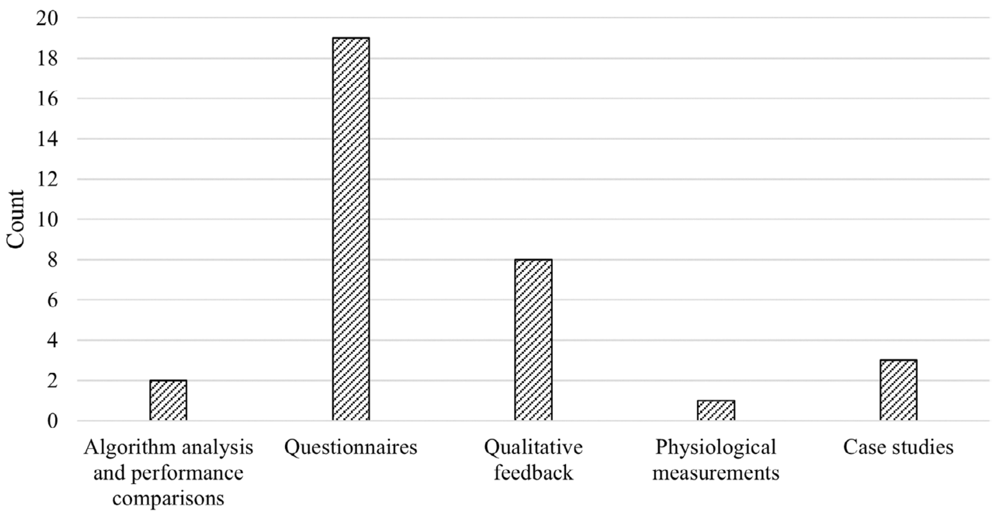


**FIGURE 8** | Testing methods.

## 4.7 | Testing and Evaluation Findings

Nineteen studies have demonstrated the effectiveness of these applications for educating and training learners about various wildfire knowledge items and skills. Moreno et al. (2014) stated that their VR fire simulation tool could adapt to the complex dynamics of wildfire spread and extinguishment, providing realistic, interactive training environments and improving trainees' readiness for firefighting. Clifford et al. (2018) compared and tested three display technologies: VR, CAVE and HDTV. They found that the immersive experience of VR aerial firefighting training significantly enhanced spatial awareness, which in turn significantly impacted the effectiveness of the training. Aldunate et al. (2019) suggested that the use of serious games for training could significantly enhance the decision-making capabilities of individuals involved in emergency management, preparing them for real-life situations. Kankanamge et al. (2022) demonstrated significant improvements in knowledge and awareness about wildfire management and preparedness after implementing the gamified application. Kazanidis et al. (2018) claimed that their AR tool could significantly increase learners' knowledge about wildfire prevention and management, first aid in extreme temperatures and emergency calls. Taylor et al. (2025) demonstrated that a 360° virtual tour effectively enhanced understanding of wildfire treatments among over 1200 participants. The study showed strong self-reported learning gains and broad support for VR as a tool to promote awareness and engagement in wildfire risk mitigation.

Several studies ($n = 11$) have also displayed the effects of the applications on motivation, attitudes and perceptions. Molan et al. (2022b) argued that their VR system could effectively engage participants to enhance their understanding of wildfire risk and motivate them to take practical steps to improve their preparedness (Molan et al. 2023). Meijers et al. (2023)

**TABLE 2** | Comparisons and learning outcomes for the meta-analysis studies.

| ID | Study | Group 1 | Group 2 | Learning outcomes |
|---|---|---|---|---|
| 1 | Meijers et al. (2023) | VR-post | Article-post | Risk perception |
| 2 | Meijers et al. (2023) | VR-post | Video-post | Risk perception |
| 3 | Clifford et al. (2018) | VR-post | HDTV-post | Situation awareness (Level 1—Perception) |
| 4 | Clifford et al. (2018) | VR-post | SimPit-post | Situation awareness (Level 1—Perception) |
| 5 | Clifford et al. (2018) | VR-post | HDTV-post | Situation awareness (Level 2—Comprehension) |
| 6 | Clifford et al. (2018) | VR-post | SimPit-post | Situation awareness (Level 2—Comprehension) |
| 7 | Clifford et al. (2018) | VR-post | HDTV-post | Situation awareness (Level 3—Prediction) |
| 8 | Clifford et al. (2018) | VR-post | SimPit-post | Situation awareness (Level 3—Prediction) |

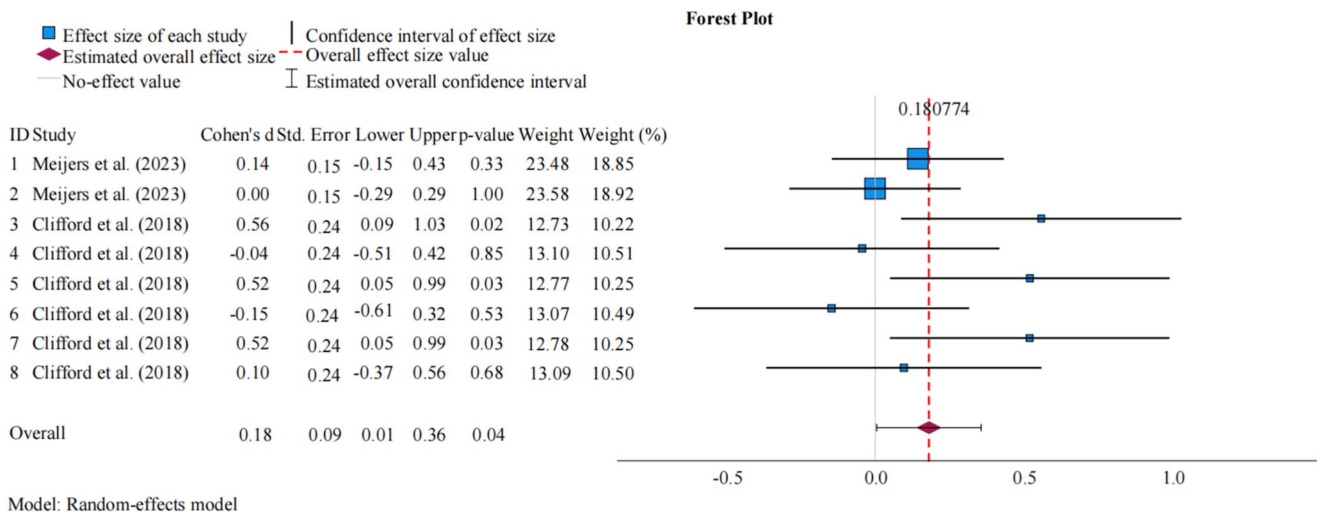


**FIGURE 9** | Forest plot of the random effects model evaluating the effectiveness of different wildfire education methods and simulation platforms (Cohen's *d*).

found that their VR application could have an impact on risk perceptions; however, additional intervention might still be necessary to have a long-term impact on behavioural changes. Kankanamge et al. (2022) suggested that their serious game could effectively increase public awareness and educate learners about wildfire risks and management strategies in an engaging and informative manner. Kazanidis et al. (2018) emphasised that using AR technology and comics for teaching wildfire prevention and management can increase learners' engagement and interest. They highlighted that the combination of innovative tools along with visually appealing comics motivated learners to engage more deeply with the educational materials. Vigna et al. (2024) demonstrated that the serious game enhanced stakeholder motivation, shifted attitudes towards collaboration, and improved understanding of wildfire risk and land management challenges, highlighting its value as both an educational and engagement tool.

## 4.8 | Meta-Analysis

This study presents a meta-analysis to detect the effect size of the gamification applications on learning outcomes. Only two articles present the complete information on sample size, mean scores and standard deviations for learning outcomes after using gamification applications (Meijers et al. 2023; Clifford et al. 2018). These two studies demonstrate multiple comparisons between immersive VR applications (i.e., HMDs) and non-immersive approaches (e.g., video, article and 2D or 3D). As a result, this meta-analysis featured eight comparisons (Table 2), focusing on the effectiveness of learning outcomes immediately after learning, including risk perception and situation awareness. The meta-analysis used the random-effects model in IBM SPSS Statistics v.30, generating Forest Plots (Figures 9 and 10).

Both Cohen's *d* (Figure 9) and Hedges' *g* (Figure 10) were used to measure the effect size. The overall effect size measured by Cohen's *d* is 0.18 (95% confidence interval: 0.01–0.36, $p = 0.04$). Similarly, Hedges' *g* was used to adjust for small sample bias, showing the effect size of 0.18 (95% confidence interval: 0.01–0.35, $p = 0.04$). According to the interpretation guidelines of Durlak (2009), these values indicate a small overall effect. However, effect sizes vary across comparisons. For instance, the studies (IDs 3, 5 and 7 in Figures 9 and 10) of Clifford et al. (2018) reported moderate effects (i.e., $g = 0.51$ and 0.55) when comparing immersive VR to HDTV for various levels of

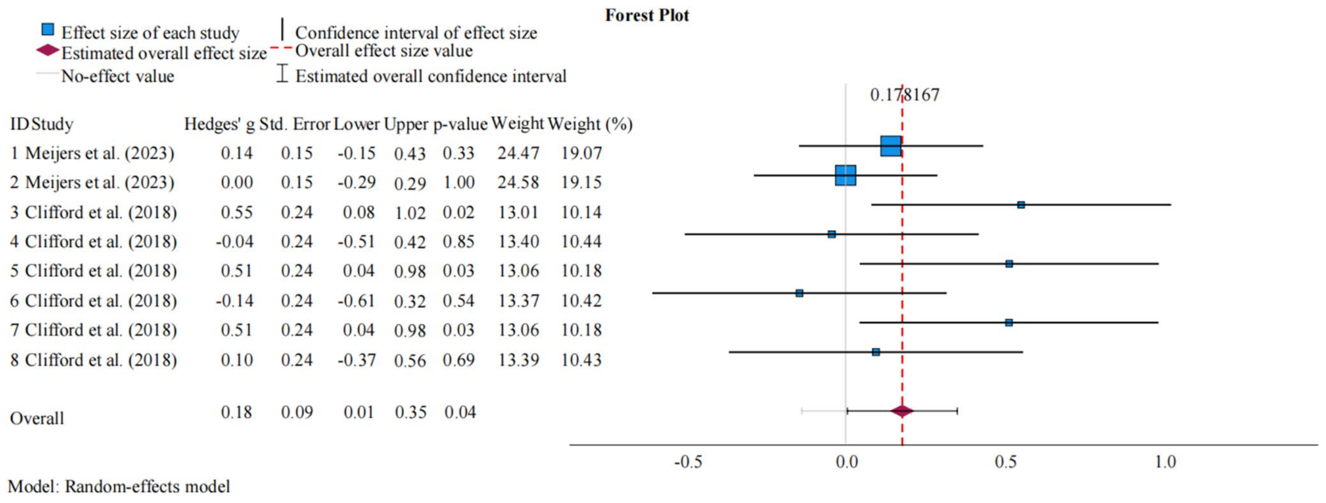


**FIGURE 10** | Forest plot of the random effects model evaluating the effectiveness of different wildfire education methods and simulation platforms (Hedge's *g*).

**TABLE 3** | Cohen's *d* for paired samples pre-post gamification intervention.

| ID | Study | Learning outcomes | Cohen's *d* ($r=0.3$) | Cohen's *d* ($r=0.5$) | Cohen's *d* ($r=0.7$) |
|---|---|---|---|---|---|
| 1 | Pereira et al. (2014) | Prevention measure awareness (Topic 1) | 0.98 | 1.16 | 1.49 |
| 2 | Pereira et al. (2014) | Prevention measure awareness (Topic 2) | 0.69 | 0.79 | 0.94 |
| 3 | Pereira et al. (2014) | Prevention measure awareness (Topic 3) | 0.67 | 0.79 | 0.96 |
| 4 | Pereira et al. (2014) | Prevention measure awareness (Topic 4) | 0.83 | 0.95 | 1.15 |

situation awareness. This result indicates that the immersive VR experiences may enhance spatial awareness significantly in wildfire training. Interestingly, when comparing immersive VR to simulators (270° SimPit), Clifford et al. (2018) found negligible, even negative effects (IDs 4, 6 and 8 in Figures 9 and 10). This finding demonstrates that immersive VR may not consistently outperform other educational approaches, and its impact may depend on the specific learning outcomes. Similar findings have been observed in other disaster-related environments. For example, Kinateder et al. (2013) compared a VR-based behavioural training group with an information-booklet group and a no-training control group in a tunnel fire scenario. They found that the VR group exhibited significantly faster and more effective evacuation behaviour. This supports the view that immersive approaches can offer advantages over informational methods, though their benefits may vary depending on the tasks and environments.

In addition to the comparison between immersive and non-immersive learning, Pereira et al. (2014) presented the sample size, mean and standard deviation of learning outcomes on wildfire prevention measure awareness before and after the learning using their gamification application. In other words, this study demonstrated the pre-post comparison. Previous studies have pointed out that meta-analysis of single-arm pre-post studies is inappropriate, as standardised mean difference does not account for the correlation between the pre- and post-measurements (Burgess et al. 2024; Cuijpers et al. 2017). Instead, standardised mean change should be used to account for such correlation. However, individual paired datapoints are not reported in (Pereira et al. 2014), leaving the exact correlation unknown. Therefore, Table 3 presents Cohen's *d* for paired samples using typical assumptions about correlation ($r=0.3$, 0.5 and 0.7). The results suggest that gamification could mostly have a large effect size ($d>0.8$) on learning outcomes immediately after the intervention.

## 5 | Discussion

### 5.1 | Overview of Main Findings

This paper provides a systematic literature review on gamification for wildfire education and training. This study focuses on analysing gamification elements in wildfire education and training applications, which presents a different perspective compared to existing review studies focusing on wildfire visualisation (Cortes et al. 2024). As such, it provides a comprehensive understanding of gamification for wildfire education compared to studies investigating gamified applications for emergencies and disasters. This was achieved by identifying and analysing 38 studies from the literature.

The use of advanced display methods such as VR, AR and 2D or 3D animations demonstrates a strong emphasis on enhancing engagement and interactivity in wildfire education. Monitors remain the most widely used in wildfire education applications, particularly for presenting 2D and 3D animations. Monitors are flexible, accessible and compatible with various simulation tools, making them a practical choice for delivering wildfire knowledge to different audiences. In turn, VR is implemented through HMDs and CAVE, which can provide immersive experiences for learners with realistic wildfire scenarios. This reliance on monitors emphasises the user-friendliness of traditional platforms, and the increasing adoption of VR highlights a shift toward experiential learning approaches. This shift trend is consistent with the findings of Holly et al. (2021). They emphasised the potential of VR to transform traditional learning into interactive and experiential formats.

Simulation methods mainly include vector-based simulations and raster-based simulations. These methods play an important role in representing wildfire behaviour realistically, enhancing the realism of wildfire education applications. However, the educational purpose they focus on is largely limited to wildfire propagation. Other educational purposes, such as evacuation planning, prevention measures, extinguishment efforts and preparedness strategies receive comparatively less attention. Additionally, while these applications target diverse audiences, their focus remains primarily on individual education, with limited emphasis on community-level education.

The analysis of 38 studies on wildfire applications revealed that 20 papers explicitly identified the gamification elements they employed. Another 15 papers indirectly incorporated gamification elements into their applications. The most common gamification element in these studies is real-time feedback (Figure 7). Real-time feedback gives learners real-time information and situational changes and helps them rectify incorrect responses and consolidate knowledge. This finding is consistent with that of Feng et al. (2018), who suggested that providing real-time feedback is an effective way to enhance the knowledge acquisition of learners.

In terms of evaluation, various methods were used to assess the effectiveness of the wildfire applications, including questionnaires, qualitative feedback and case studies. Questionnaires, particularly pre-tests and post-tests, were the most common tool for measuring knowledge acquisition and retention. The findings of the evaluations revealed the effectiveness of these applications in educating learners on various wildfire-related knowledge and skills, such as enhancing learners' preparedness skills and improving crisis awareness.

Additionally, this study found that gamification elements used in wildfire applications improved learners' engagement and motivation. This is consistent with gamified applications for other fields. For instance, Chittaro and Buttussi (2015) emphasised that gamification elements significantly increased engagement and motivation, contributing to better knowledge retention compared to traditional methods. Kazu and Kuvvetli (2023, 2025) found that gamified learning platforms such as Duolingo significantly improved a range of language competencies. These findings suggest that gamification can support diverse cognitive skill development, reinforcing its potential value for wildfire education.

## 5.2 | Current Gaps and Future Research Directions

This study found several gaps that are worth future investigation. First, most studies have paid a lot of attention to generating and presenting realistic wildfire simulations across various platforms, including VR, AR, monitors and other interactive systems. For instance, some studies used wildfire simulators to demonstrate the wildfire spread accounting for slope, wind and fuel density and employed particle systems to model smoke and flame dynamics (Castrillón et al. 2011; Huang et al. 2012). Some studies created virtual environments to provide immersive experiences of wildfire spread (Lewis et al. 2020; Meng, Lu, et al. 2023). Although learners could still learn about wildfire behaviours through these applications, the knowledge about evacuation, prevention and response measures was neglected. More importantly, the current studies rarely assess key pedagogical outcomes such as knowledge retention and long-term behavioural change. Only a few studies attempt to incorporate such outcomes into simulation-based learning. Future research should go beyond the visualisation of wildfire dynamics and examine how realistic simulations can be used not only to teach fire behaviours but also to promote sustained learning and preparedness measures.

Second, there was no study that explicitly indicated the use of learning theories to guide and support their applications for educating learners, but one study applied theories related to learning, highlighting the potential of such frameworks in enhancing educational outcomes (Howe et al. 2018). Learning theories explain how people acquire, process, retain and recall knowledge by focusing on internal and external influences (Schunk 2012), providing valuable insights for designing more effective educational interventions. For instance, the integration of learning theories into gamification can align the educational content with targeted learning outcomes, ensuring deeper engagement and knowledge retention (Abd El-Sattar 2023). Wildfire safety encompasses a wide knowledge domain and skillset, which is challenging for education, especially for having long-term impacts. Despite the potential of gamification to address these challenges, current applications lack the theoretical foundation to ensure learning effectiveness and engagement. Future research should pay more attention to applying and testing different learning theories to gamification applications targeting wildfire education and safety training. Additionally, future research should also investigate how individual gamification elements, such as feedback, role-playing, or difficulty levels, can be linked to specific learning theories. This alignment would help clarify their distinct effects on cognitive and affective learning outcomes and inform the design of more theory-driven educational tools.

Third, this study found that many studies targeted the general public as their audience; however, few studies mentioned community-level education specifically (Howe et al. 2018; Kankanamge et al. 2022; Pereira et al. 2014). Community education is critical for wildfire preparedness (Agrawal and Monroe 2006). It supports efforts to reduce fuel sources and improve resilience through defensible space, fire-resistant materials, landscape maintenance and community planning (Maranghides et al. 2022). Focusing only on individual education may result in isolated preparation, which may cause misaligned information and miscommunication (Fu and Zhang 2024). Individual-level education primarily enhances personal awareness and preparedness actions, such as clearing flammable materials or creating a personal evacuation plan. On the other hand, community-level education emphasises collective actions, resource allocation and sharing and coordinated planning, such as joint emergency response planning and long-term cooperation. Social learning theories suggest that learning within a community can strengthen trust (Reed et al. 2010), communication and cooperation, which are crucial for wildfire management. Wildfire management often requires coordinated responses; thus, a lack of coordinated efforts and resources may lead to ineffective responses (Fu and Zhang 2024; Synolakis and Karagiannis 2024). Simply educating and training every individual in a community does not necessarily constitute community-level education unless it emphasises collaborative learning, shared responsibility and coordinated actions. One promising direction for addressing this issue is to focus more on community-level education, which may build a foundation for long-term resilience and sustainable development. Integrating social learning theories can further enhance the effectiveness of wildfire preparedness strategies by strengthening community bonds and facilitating the diffusion of knowledge. Potential gamification approaches, such as multiplayer simulation games or collaborative role-playing scenarios, could encourage active participation, peer learning, and community-wide engagement in preparedness activities (Oliveira et al. 2015).

Fourth, this review found limited attention paid to wildfire prevention measures in existing applications (Vega et al. 2017; Bolijn et al. 2022; Kazanidis et al. 2018). Most studies primarily focus on wildfire propagation and raising awareness. However, few aim to educate people on prevention measures such as fuel management, spatial reservation for firebreaks and fire-resistant design. Prevention plays a significant role in effective wildfire risk management by reducing both the probability and severity of wildfires before they occur (Calkin et al. 2014). The importance of prevention was tragically highlighted by the 2025 Los Angeles wildfires, as fast-spreading fires driven by unmanaged vegetation and insufficient defensible space resulted in extensive property damage and significant loss of life (Horton et al. 2025). This event highlights the urgent need to increase long-term wildfire prevention awareness. Future research should investigate how to integrate prevention-focused content into wildfire education applications, particularly through interactive and gamified approaches that promote long-term behavioural change.

Finally, a significant gap lies in the practical implementation of gamified wildfire education programs, particularly those involving immersive technologies. Although immersive technologies such as VR and AR have shown great potential in enhancing learner engagement and realism, their development and deployment remain challenging (Westera 2019). These advanced applications often require costly hardware, high-speed and stable internet and digital literacy, which may not be feasible for schools and in rural or underfunded regions. As a result, the feasibility, accessibility and scalability of gamified wildfire education programs remain critical concerns. However, emerging evidence suggests that immersive technologies may help overcome some barriers to behavioural training, particularly for types of training that are difficult to deliver through traditional instruction. With the decreasing cost and increasing portability of VR headsets, it might be cheaper and more feasible to distribute headsets to remote communities than to dispatch human coaches (Berthiaume et al. 2024). Future research should focus on highly inclusive and low-cost wildfire gamification strategies, such as mobile or web-based platforms (Pereira et al. 2014) and the strategic use of affordable VR, to ensure broader access and practical adoption. This becomes particularly relevant and necessary with the rapid evolution of artificial intelligence happening nowadays, as AI is dramatically reshaping the development and implementation of different technologies.

### 5.3 | Practical Implications

This review offers several practical insights for stakeholders involved in wildfire education and training. For educators, the integration of gamification can support more engaging and experiential learning. Specific skills and knowledge that directly support educational goals, such as how to plan evacuations or identify wildfire hazards, can be taught more effectively through gamification. Educators could consider incorporating simulation-based or gamification tools to improve student motivation and knowledge retention (Kazanidis et al. 2018). For emergency service trainers such as firefighters, immersive technologies (e.g., VR and AR) can provide a safe environment to enhance situational awareness and decision-making under pressure (Heyao and Tetsuro 2022). Also, using immersive technology may deliver better learning outcomes than non-immersive learning, which is shown in the meta-analysis results (Figures 9 and 10). For policymakers and programme developers, it is important to consider the feasibility, accessibility and scalability of gamified wildfire education programmes, especially in under-resourced or rural communities (Pereira et al. 2014). Additionally, community-level activities such as collaborative online simulations (Oliveira et al. 2015) can foster shared responsibility and build collective resilience.

### 5.4 | Academic Novelty and Contribution

This study makes some novel academic contributions to the field of gamification in wildfire education and training. First, unlike previous reviews that focused on wildfire modelling or emergency simulation (Liu et al. 2015), this is a new systematic review to specifically examine the application of gamification elements in wildfire education and training. This study offers a more targeted and actionable understanding of how gamification is currently employed and evaluated in this context. Second, a key finding of this review is the lack of integration of learning theories in existing gamified wildfire applications. This review proposes a theory-driven research agenda, encouraging future work to align gamification elements with learning theories such as constructivism and behaviourism. Finally, this study employed VOSviewer to visually map current research focuses and emerging trends in the field. In addition, it conducted a meta-analysis to compare the effectiveness of immersive versus non-immersive approaches within wildfire education, which received limited attention in previous research. This study used SPSS to reveal a small but significant effect size ($g = 0.18$), which aligns with the game-based learning in other fields. For instance, Sailer and Homner (2020) reported small to moderate effects of gamification on cognitive ($g = 0.49$), motivational ($g = 0.36$) and behavioural ($g = 0.25$) learning outcomes across diverse educational domains. These quantitative findings are paramount to run power analysis for future studies testing new gamification solutions for wildfire education. The combination of qualitative and quantitative analysis in this study strengthens the reliability of the findings and provides a more robust foundation for future research.

### 5.5 | Limitations

This study holds some limitations. This review does not cover the papers that describe gamified education programs that are not digital applications or games. By excluding non-digital gamified education, the review may have missed insights from broader gamification practices in education. Non-digital applications or games used in classrooms or communities can also provide valuable perspectives on gamified learning. This limited scope may result in an incomplete understanding of gamification in education. Moreover, this review does not compile sufficient data to analyse the effect size of gamification on education and training. Without such analysis, it is challenging to draw strong and reliable conclusions about the effectiveness of gamification. Identifying specific variables that may enhance or diminish the effectiveness of gamification in education and training is also challenging. Additionally, this review primarily focuses on existing gamification applications and their current functionalities. However, it does not extensively explore whether these applications can be updated periodically. Such updates are necessary as mitigation knowledge continues to evolve.

## 6 | Conclusion

In this study, a systematic literature review is presented on gamification in wildfire education and training. This work identified existing forms of wildfire education applications as well as their benefits and limitations. Display methods and platforms, simulation methods, educational purposes, gamification elements, and learning outcomes and measurements were analysed. The findings indicate various effects of different gamification solutions on the effectiveness of education and on learners' motivation and experiences. In summary, this study contributes to knowledge by offering a comprehensive understanding of the field, identifying critical research gaps and proposing clear directions for future work. Practically, it also provides actionable recommendations to guide the design of more effective and engaging gamified educational interventions.

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#### Author Contributions

**Tianqi Huang:** writing – review and editing, writing – original draft. **Zhenan Feng:** funding acquisition, writing – review and editing, supervision. **Daniel Paes:** writing – review and editing, supervision. **Fei Ying:** writing – review and editing. **Xilei Zhao:** writing – review and editing. **Max Kinateder:** writing – review and editing. **E. R. (Lisa) Langer:** writing – review and editing. **Ruggiero Lovreglio:** writing – review and editing, supervision.

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#### Conflicts of Interest

The authors declare no conflicts of interest.

#### Data Availability Statement

Data sharing is not applicable to this article as no data sets were generated or analysed during the current study.

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