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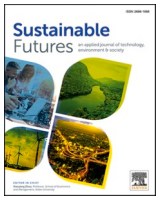

Gamification and sustainability: A review of approaches for urban mobility and climate change resilience

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ABSTRACT

The global urbanisation trend is exacerbating environmental issues and demanding innovative solutions. In this context, the role of human behaviour is increasingly significant, hence it is crucial to increase awareness and promote behavioural change. This systematic literature review explores the critical intersection of sustainable mobility and climate change resilience within urban contexts, focusing on the transformative potential of gamification to drive behavioural change. Sustainable mobility mitigates climate impacts by reducing emissions, while climate change resilience ensures transport systems can withstand environmental disruptions. Integrating these two concepts is crucial for a climate-secure urban future.

The research findings highlight the underexplored potential of Artificial Intelligence techniques for tailoring the gaming experience to the user or context, the need for a more diverse geographical distribution of studies, and the lack of attention given to the characteristics and needs of target users. Further, this review identifies the lack of studies combining sustainable urban mobility and climate change resilience.

1. Introduction

Urbanisation is increasingly shaping our world, with significant effects on the environment. According to the United Nations, over 55 % of the global population currently resides in urban areas, with projections increasing to approximately 70 % by 2050.[1] This unprecedented urban growth brings us opportunities and challenges for sustainable development. Urbanisation drives economic growth and innovation, yet it exacerbates sustainability and climate change consequences, by aggravating environmental issues like air pollution, traffic congestion, air temperature increase, and resource depletion [1–3]. Further, the land-use changes associated with the urban expansion cause significant environmental consequences in itself, such as ecosystem degradation and disruption of hydrological cycles and biodiversity [4]. Within this context, city authorities are proactively implementing policies to mitigate climate change and enhance human wellbeing [5]. However, policies alone cannot play a major role if there is not a significant behavioural change that supports and implements them. For this reason, the role of human behaviour in addressing urbanisation-related issues has become increasingly significant [6]. Because of the importance of human behaviour, this analysis focuses on the intertwined relationship between sustainable mobility and climate change resilience [7,8] through the lens of gamification, an increasingly employed engagement technique known to facilitate behavioural change.

Sustainable mobility, which encompasses modes like walking, cycling, public transport, and electric vehicles, primarily mitigates some of climate change consequences by reducing greenhouse gas emissions from the transport sector, a major contributor to global warming [9]. Climate change resilience focuses on adapting transport systems and infrastructure to withstand and recover from the inevitable impacts of a changing climate, such as extreme weather events like floods and heatwaves [10]. These two concepts, mitigation and adaptation, must be considered together as they share a number of objectives including multimodality and diversity of transport modes and social equity [11]. More concretely, mitigation efforts from sustainable mobility can help reduce the severity of future climate impacts, thereby lessening the burden on resilience measures [12]. Conversely, a resilient transport system ensures that sustainable mobility options remain viable and accessible even during climate-related disruptions [13]. Integrating both approaches in planning and investment provides a cost-effective

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[1] https://www.un.org/uk/desa/68-world-population-projected-live-urban-areas-2050-says-un

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and holistic path toward a climate-secure future for our cities and communities, and ensures that synergies are maximised [14].

In this context, gamification [15], as the application of game-design elements in non-game contexts, has emerged as a promising approach to motivate, engage, and educate individuals to adopt sustainable behaviours [16,17], and to facilitate conversations and identify solutions within companies and institutions involved [18]. By leveraging the intrinsic and extrinsic motivations inherent in games, gamification can effectively influence human behaviour and foster a culture of sustainability. The growing interest in applying gamification to climate change challenges underscores its potential to drive behavioural change and support sustainable development goals.

Existing related literature reviews investigated behaviour change in sustainable mobility developing a conceptual model that includes smartphone-based gamified solutions [19], explored the use of video games for urban planning decision making and climate change education [20], or analysed digital tools for pro-environmental engagement in urban contexts [21]. Yet, holistic and integrative analyses regarding these two previously disconnected domains, and the role of gamification in this context, is lacking.

This literature review aims to explore the potential of gamification in addressing sustainable urban mobility and climate change resilience challenges, highlighting the synergies between these two domains. By analysing existing literature and case studies, this review seeks to provide a comprehensive understanding of how gamification has been utilised, and to inform the future research agenda for improving sustainability in urban areas.

2. Methodology

This paper analyses the current literature on gamification in the context of sustainable urban mobility and climate change resilience through a systematic qualitative literature review, or meta-synthesis [22,23]. The PRISMA framework was employed, ensuring transparency and reproducibility of the research [24], and the search was conducted in Scopus.

2.1. Keywords

To capture studies that exploit gamification approaches in the fields of sustainable mobility and climate change resilience, the following comprehensive list of keyword sets has been used.

("gamification" OR "game" OR "game-based" OR "gamify" OR "game-style feature" OR "interactive element" OR "applied game design" OR "incentive-centered design" OR "incentive-centred design" OR "playful design" OR "reward system") AND ((("sustainable" OR "eco-friendly" OR "green" OR "environmentally responsible" OR "environmentally friendly" OR "ecological" OR "renewable" OR "resource-efficient" OR "recourse efficiency" OR "low-emission vehicle" OR "low-carbon vehicle") AND ("urban" OR "metropolitan" OR "municipal") AND ("transportation" OR "transport" OR "mobility")) OR (("climate change" OR "climate adaptation" OR "climate mitigation" OR "climate risk" OR "climate crisis" OR "climate" OR "environmental") AND ("resilience" OR "adaptability")))

2.2. Screening, eligibility, and exclusion

The literature selection follows the PRISMA framework (depicted in Fig. 1). Only peer-reviewed journal papers in English language were included in the initial search, as they served the main source of empirical evidence [25] for the investigated topic. The search was conducted between January-April 2025, and no timeline restrictions were applied to the search.

As a result, 375 studies were returned from the Scopus database, with 2 duplicate records, and 1 conference abstract, which were removed. A journal quality criterium was then applied, which filtered out 35 papers ranked in Q3 or Q4 in the latest SJR list. After that, 337 abstracts were reviewed to screen out papers not related to (1) gamification, (2) sustainable transport, or (3) climate change resilience topics, which

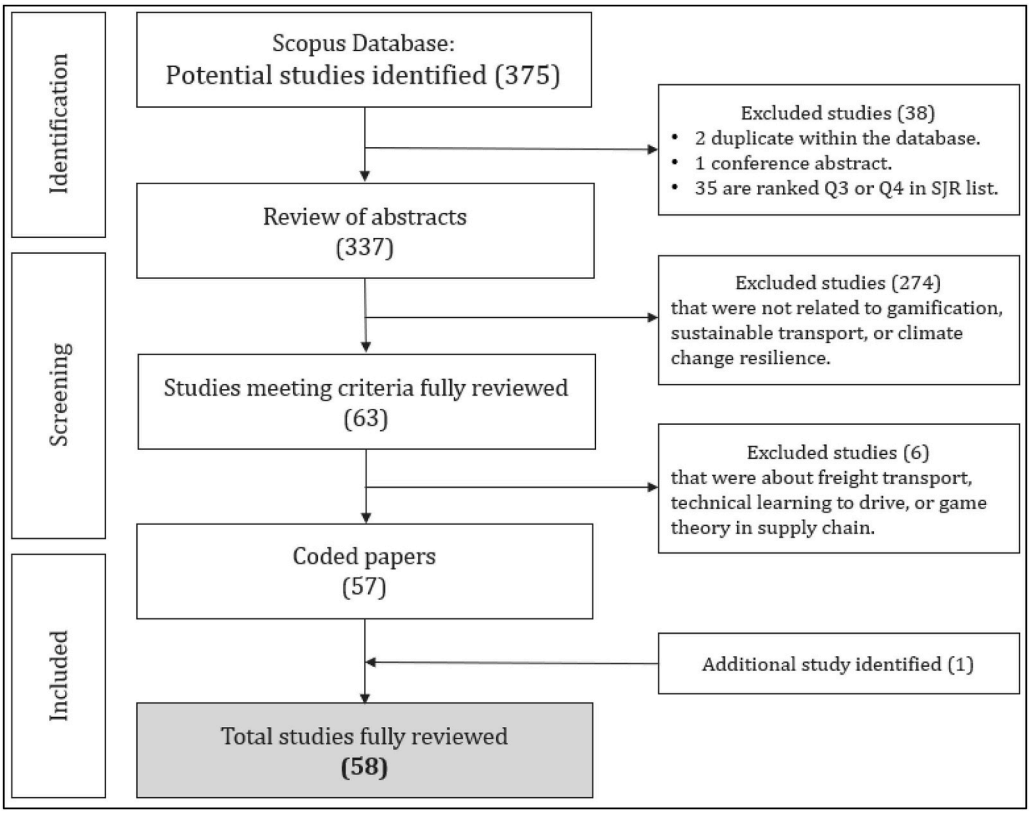

Fig. 1. Papers selection process using the PRISMA framework.

resulted in 63 papers left for full-text review. The abstract screening was done by two independent researchers and cross-checked by a third researcher to minimise bias and enhance consistency.

Full-text review was conducted, which further screened out 6 papers (as out of topic e.g., about freight transport, technical learning to drive, or game theory in supply chain). Finally, 1 paper was added from the backward snowballing search of included papers' references lists. In total 58 papers were coded, analysed, and considered in this systematic review.

3. Results

This section presents the results of the performed literature review, and is structured around five areas, namely, Type of games and incentives (Section 3.1), Target area of the studies (Section 3.2), Target users (Section 3.3), Goals that the approaches aim to achieve (Section 3.4), and Metrics used to measure the success of the designed solutions (Section 3.5). The decision to focus the analysis on these areas was made to give a compelling overview of what has been studied so far and helps identify future directions.

3.1. Type of games and incentives

Among the various gamification approaches that researchers use to engage stakeholders in sustainable mobility and climate change resilience, serious games appear to be most prevalent and effective. Serious games are full-fledged games with rules and quantifiable outcome expectations, designed for educational, training, and behavioural change purposes [20,26].

Serious games differ from casual games [20] that are for entertainment purposes with minimal commitment [27]. Examples of casual games are Gustafsson et al.'s [28] mobile pervasive games that are designed for fun, creating an enjoyable learning experience to encourage energy-saving behaviours among teenagers, or Boncu et al.'s [29] gamified self-directed learning app to influence students' sustainable behaviours. These casual games feature simple mechanics, focusing on entertainment-driven approaches and have a light touch on educational purposes. The review identified that the most common game structure is serious game, therefore, this paper focuses on understanding the main characteristics and differences of these serious games and not consider casual games.

In the context of sustainable mobility and climate change resilience, serious game is an overarching term which does not refer to a specific gameplay mechanic, and although the overarching goals can be similar (e.g., behavioural change, education purposes, or participants' engagement) the specific mechanics can differ. Therefore, it is important to understand what different approaches were used in their implementation.

When reviewing papers, the games were categorised based on the platforms used to design and deliver them (e.g., web-based, in person). 34 papers were identified as studying games delivered through digital platforms, 16 papers focused on in-person and physical games, 5 papers on hybrid games, and 3 papers on general discussion regarding gamification.

Fig. 2 depicts the distribution of game types. The inner ring shows the main categories: digital, physical, hybrid, and other types. The outer ring breaks each category down into its specific delivery medium. The size of each segment represents the number of studies in that category or subcategory. It can be seen that digital games dominate the landscape, especially mobile-based formats. Physical games, particularly board games, still hold a significant share, highlighting their continued relevance. Yet, hybrid models are emerging, indicating an interesting trend toward combining digital and in-person experiences. Table 1 summarises different types of games studied in the reviewed literature, together with their incentive types.

A detailed analysis of digital, physical, and hybrid games that were identified in the literature is presented in the following sections

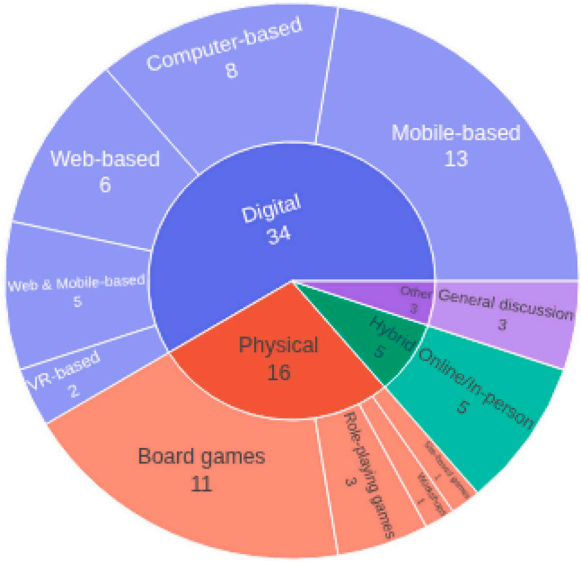

Fig. 2. distribution of gamification platforms and delivery mediums.

3.1.1. Digital games

Digital games in gamification research refer to interactive systems that leverage digital technologies to deliver game-like activities and experiences [84,85]. These games require certain technology infrastructure and often involve real-time feedback and data tracking [85].

The delivery media include mobile-based games (13 papers), computer-based games (8 papers), web-based games (6 papers), hybrid media of web and mobile games (5 papers), and virtual reality (VR) games (2 papers). With the advancement of technologies such as artificial intelligence (AI), digital games are gaining momentum due to their ability to offer a more personalised and immersive experience to users [86]. Types of digital games are detailed below.

3.1.1.1. Mobile-based games. In digital games, the most studied are mobile-based games, discussed in 13 papers. Mobile-based gamification refers to the use of game-like elements delivered via mobile applications, and in the reviewed literature, this type is heavily anchored in transportation-related topics, promoting sustainable mobility and environmentally friendly behaviours.

These games provide users with a mix of extrinsic and/or intrinsic incentives. The use of incentives is recognised to enhance user engagement with the game and awareness of the relative issue. The most common incentives in these games are different types of rewards such as points, leaderboards, prizes, and badges (e.g., [32,33]), with digital tokens, points, or coins working well due to the nature of these games. Together with these extrinsic incentives, some games also include some more intrinsic ones, as social recognition and community belonging ([21]), internal satisfaction, environmental identity and pride ([40]), and collaboration and competition ([38]).

As for most gamified solutions, there are some limitations in digital systems and games. First, the effectiveness of app-based games drops over time [21]. Second, there are ethical concerns related to control, use, and purpose of the data collected [40], since mobile apps rely on massive data collection of individual behaviours such as transportation, electricity use, and other private activities. Third, access to smartphones is a prerequisite to mobile-based games, and this has accessibility implications as it may exclude older or lower-income populations, areas where service is limited, or people with specific disabilities if the design of these apps does not cater for them. For example, Bruckermann [40] mentions that the digital carbon apps are primarily used by urban and

Table 1
Categorisation of games.

Platform	Delivery Medium	Count	Main Incentives	Studies
Digital	Mobile-based	13	Intrinsic: challenges, social sharing. Extrinsic: points, badges, prizes, leaderboards, discounts, community recognition.	[30–35, 19]*; [36–40, 21]*.
	Computer-based	8	Intrinsic: real-time feedback, scenario-based challenges, personal satisfaction, curiosity, learning, competition. Extrinsic: points, lottery rewards, penalties.	[41–48].
	Web-based	6	Intrinsic: feedback, challenges, goal tracking Extrinsic: points, prizes, leaderboards, certificates	[49–54].
	Both web- & mobile-based	5	Intrinsic: real-time feedback, humour and satire. Extrinsic: credits, points, levels, badges, leaderboards	[55–57, 20]*; [58].
	Virtual Reality (VR)-based	2	Intrinsic: Visual feedback, modular learning, discovery, hypothesis testing. Extrinsic: none.	[59,60].
Physical	Board games	11	Intrinsic: challenges, collaboration, immediate feedback, awareness building and knowledge sharing, community engagement, learning motivation. Extrinsic: in-game rewards.	[61–65, 27, 66–70].
	Non-board role-playing games	3	Intrinsic: social learning, scenario-based challenges, discussion and reflection. Extrinsic: recognition.	[71–73].
	In-person workshops	1	Intrinsic: joy, self-expression, creativity. Extrinsic: N/A.	[74].
	Site-based participatory games	1	Intrinsic: community empowerment, co-creation of interventions. Extrinsic: N/A.	[75].
Hybrid of physical and digital	Online platform / In-person workshops	5	Intrinsic: empowerment, learning, risk-reward trade-offs, scenario testing. Extrinsic: Monetary-like budget system.	[76–80].
Other types	General discussion	3	Intrinsic: N/A. Extrinsic: rewards and points.	[81–83].

Note: * refers to a literature review of the certain type of the game without developing or implementing gamified empirical study.

middle-class consumers, implying the exclusion of rural, older, and/or lower-income people. Fourth, the generalisability of the digital games is another limitation, and as demonstrated by Ferron et al. [35], to generate a broader adoption, localisation, personalisation, and multilingual choices are strategically essential.

3.1.1.2. Computer-based games. Computer-based games are considered in 8 of the papers revised. Computer-based gamification refers to the use of game-like elements delivered via computer/laptop to enhance user experience either in a laboratory environment (e.g., [41,43,44]) or on any individual computer (e.g., [48]). These games appear the most in papers focusing on sustainable mobility and climate change resilience, and all tend to leverage the simulation mechanics with some role-playing elements.

Due to the interactive nature of computer-based games, simulation games can model real-world situations, systems, or phenomena, allowing participants to experiment with interventions. According to the descriptions and rules of the games detailed in the literature, it seems that simulation-based games put more emphasis on realism, requiring participants' systematic thinking and decision making under different circumstances. For example, when facing simulated complex systems, such as traffic congestion and parking (e.g., [41,43]), players need to decide how to park or when to carpool; or in the simulation of various natural hazards (e.g., [47]), players analyse the effectiveness of emergency services and damage mitigation strategies. Realism in simulation games is what allow users to achieve learning goals, as congruence between the game and the reality is key for their thinking process [87].

Incentives in computer-based games are predominantly intrinsic motivation, leveraging elements such as real-time feedback and penalties (e.g., [41]). Extrinsic incentives also appear in some papers such as points (e.g., [48]), lottery rewards (e.g., [44]) or certificate and coupons from city authorities (e.g., [42]), while other papers do not have direct user incentives (e.g., [45,46]).

3.1.1.3. Web-based games. Web-based games are discussed in 6 papers. The main difference between web and computer games is that the former type integrates game mechanics into online platforms accessible via web browsers with stable internet connectivity [49], while the latter is often software-based and can be played offline on computers. This type is predominantly mentioned in climate change resilience papers where complex systems are simulated to understand behavioural adaptation [49], raise awareness [51], or train decision-makers [54].

The design of reviewed web-based games is user-centred, often incorporating real-time feedback, and enabling immersive learning experiences [53]. In Demiray et al.'s [50] work, players interact with a game based on real-world data such as flood risk, and their decision-making regarding whether and where to build flood defences is an immersive gameplay and scenario-based learning. Additionally, web-based games are a safer experimentation. As mentioned by Demaree et al. [52], the games serve as the testing platform of policy refinement before real-world implementation.

Web-based games incentives vary based on purposes, contexts, and audience. Specifically, scenario-based feedback is the most immediate incentive to drive engagement and learning (e.g., [49]), and monetary rewards can lead to more sustainable behaviours (e.g., [52]). Like other extrinsic incentives, points and rewards (e.g., [52,53]) are also used in this type.

These games can have some accessibility limitation like complicated interface (e.g., 3D mini-game [53], and the need for higher-end device and connectivity to play (such as [51,53]).

3.1.1.4. Hybrid media of web and mobile games. 5 papers focus on games used through hybrid media of both web- and mobile-based games. This hybrid mode allows users to interact with the game across devices and contexts, for example, back-office users can access the web application

while other users may use the mobile version on the go [55].

Their incentives are similar to other games, including intrinsic incentives such as real-time feedback (e.g., [20]) and humour and satire (e.g., [57]), and extrinsic incentives such as points (e.g., [56,57]), badges and leaderboards (e.g., [20]), and certificates and rankings (e.g., [58]).

As with other web or mobile games, this type also suffers from digital divide [88], and it may exclude certain demographics (e.g., older generations [20]).

3.1.1.5. Virtual reality (VR) games. Surprisingly, given the suitability of the technology for providing immersive experiences, Virtual Reality (VR) games are discussed in 2 papers only. The literature shows that this type of game is used in climate change resilience research, and the immersive, user-centred, and engaging nature helps raise awareness and enhance risk preparedness.

All the studies leverage intrinsic incentives such as visual feedback, modular learning, discovery, and curiosity-driven exploration [59,60], and unexpectedly little is mentioned about extrinsic incentives.

Some games require high-performance devices that can perform 3D rendering (e.g., [60]), causing inclusivity and accessibility issues, and in the meantime, this type also raises cost concerns for researchers when designing and implementing the gamified research.

3.1.2. Physical (in-person) games

Physical games, or in-person games, require physical materials or space, which emphasise tangible, social, or spatial interactions. These games facilitate face-to-face interactions, and emphasise collaborative problem-solving [89].

The delivery media include board games (11 papers), non-board role-playing games (3 papers), in-person workshops (1 paper), and site-based participatory games (1 paper). These games remain vital in raising awareness in sustainable transportation and empowering climate change resilience, and whether digital infrastructure is limited or not, traditional non-digital games are still prevalent in both developed and emerging economies. Types of physical games are detailed in the following sections.

3.1.2.1. Board games. Among physical games, the most studied are board games (11 papers). Most board games are associated with climate change resilience studies, where the purposes are to improve participants' understanding of climate risks, resilience, and/or sustainability.

These types of games can engage diverse groups of stakeholders including farmers (e.g., [69]), city administrators and municipal staff (e.g., [65]), communities (e.g., [27]), and students (e.g., [66]) among others, and incentives differ depending on the target group. Resident- and community-targeted studies focus more on intrinsic incentives such as learnings (e.g., [63]) and disaster risk awareness (e.g., [27]). For students are more effective extrinsic incentives such as game scores and performance metrics (e.g., [66]), and social incentives such as peer interaction (e.g., [66]).

Even though board games with role-playing elements appear to be effective for experiential learning and encouraging stakeholder dialogue, some accessibility issues exist. These games must be culturally appropriate and relevant for the target group [68], otherwise this could result in a lack of engagement and undermining of the collaboration.

It is worth mentioning that most board games typically involve physical components such as a board, dice, tokens, and characters, but not all board games are role-playing games (RPGs). As a matter of fact, even though most board games do assign players certain roles, some studies emphasise less on fictional roles in a board game such as those [66], where players simulate land-use decisions without specific roles, and the physical board is just a medium.

3.1.2.2. Non-board role-playing games. Most role-playing games leverage a physical board as a medium, however, there are also some studies that are narrative and scenario-driven and do not use boards (e.g., [71–73]). These 3 papers were categorised separately because they can be non-spatial in the traditional sense, and often relying on imaginative or narrative-driven environments.

Non-board role-playing games are used in educational or stakeholder engagement contexts, and participants are engaged via scenario-based, narrative, or character-driven simulations ([71–73]). They often foster experiential learning and socially encourage stakeholders to explore risk management and communication strategies [72]. However, the major limitation of this type of gamification is that it tends to simplify complex issues [72] and may not fully replicate real-world hierarchies or power imbalance among stakeholders [73].

Intrinsic incentives tend to be the predominant type in non-board role-playing games, such as social learning, challenges, discussion and reflection [73], with fewer extrinsic incentives, such as recognition [71]. It is worth noting that monetary incentives such as real-world coupons or vouchers do not appear in both board games and non-board role--playing games, and this may be due to the particular purpose of these games being mainly of social learning, policy exploration, and stakeholder dialogue.

Regarding accessibility issues, both board games and non-board role-playing games do remove some digital barriers, therefore cater for a wider demographic.

3.1.2.3. In-person workshops and site-based participatory games. The last two types of physical games are in-person workshops, discussed in one paper (i.e., [74]), and site-based participatory games, also discussed in one paper (i.e., [75]). The former is creative and expressive play-based learning to facilitate trauma healing in post-disaster situation [74], while the latter is participatory and co-creative urban design game to enhance urban climate resilience via placemaking [75].

These two types of gamification approaches use game-like structures and rules in the physical settings to achieve educational or social goals, and according to the results [74,75], they have transformative potential in addressing complex societal challenges.

However, these games also face challenges. The scalability is rather limited, because they are either cultural- and event-specific [74] or require facilitation and local stakeholders buy-in [75].

3.1.3. Hybrid of physical and digital games as well as other types

Hybrid of physical and digital gamification refers to the structured interventions that combine digital tools with in-person game play to facilitate experiential learning and collaborative decision-making. These games are often built on computation models such as NetLogo agent-based simulation [76,77], but with an in-person nature that facilitates participants' engagement.

Here incentives are both intrinsic and extrinsic, such as scenario-based challenges (e.g., [77]), empowering and learning (e.g., [79]), risk-reward trade-offs (e.g., [80]), and monetary-like budget system (e.g., [79]).

The Hybrid mode appears to combine the advantages of digital and in-person games. In [76], digital tablet-based interfaces are combined with in-person group interaction, with the use of mobile technology providing a dynamic visualisation for the participants and data collection standardisation for the researchers. Bell et al. [76] further noticed that the tablet was accessible and circumvented the infrastructural demands of internet connectivity, which were "playable at a table or in a field or under a tree" [76, p.3].

However, in this type of games, the context-specific design limits the generalisation of the games and the research findings. In the case of [76], researchers tailored the game to Pastoralists in Kenya, therefore scaling to other areas would require significant redesign of the game.

Lastly, research papers [81–83] proposed gamification as a problem-solving technique but do not implement it. These games are

categorised as other types of games in Table 3.1. For example, Marroquín-Ciendua et al. [81] suggested gamification and targeted communication as effective tools to increase the adoption of shared electric scooters in the city. Kuzyk [82] advocated for gamification and localised communication about carbon footprints to arise citizens' awareness and policy engagement. Marcucci et al. [83] proposed a user-centred gamification design framework for the purpose of increasing participation in recycling and reverse logistics.

3.2. Target area

Once the typologies of games were identified and analysed, the review focused on the target area by considering two different dimensions: the geographical distribution, highlighting the world-wide distribution of studies, and the urban vs rural distribution, focusing on the tension between these two very different environments.

3.2.1. Geographic distribution

The reviewed studies include contributions from 36 countries, with the most represented being Italy (14 cases), followed by the United Kingdom (8 cases), France (7 cases), and the United States (6 cases). The remaining countries each contribute between 1 and 5 cases, showing a broad international scope across Europe, Asia, the Americas, Africa, and Oceania. Fig. 3 visualises the geographic distribution of the case studies, with countries shaded according to the number of contributions, i.e., Italy, United Kingdom, France, and the US showing the highest representation.

Most studies focus on specific cities, towns, or communities in the researchers and participants' country of residence, which reflects a tendency to focus locally when researching mobility and climate change resilience. For example, Marroquín-Ciendua et al. [81] considered only Bogota, Colombia, when investigating public electric scooters in the context of air and noise pollution. Such approach works well for local governance and policies, but might lack scalability.

There are a few studies generalised at a national (e.g., [61,40,72,79]) or global level (e.g., [55,78,57]). For example, Bogdan and Cottar [72] aimed to enhance residents' resilience by addressing the key issues in flood risk management across nation-wide Canada, while Cook et al. [57] conducted the research in English but the game is being translated into 14 different languages aiming to support broader international use.

Noteworthily, there is a strong European presence in the geographic breadth, specifically, out of 59 reviewed papers, 35 studies[2] focused on European cities such as Lisbon [30], London [45,46]; Rotterdam [75], Trento [31,35], Palermo [32,37], Zurich and Ticino [34], accounting for 59.3 % of the reviewed literature.

3.2.2. Urban vs rural focus

In the sustainable urban mobility context, all the studies focus on the urban settings and study smart cities, mobility, and commuting behaviours. Gamified activities can significantly influence participants' travel habits towards more sustainable modes. Specifically, psychological and attitudinal changes are observed: people's perceived usefulness and attitudes towards walking and cycling are positively influenced by gamified app [31]. Additionally, behavioural shifts such as more adoption of scooters [81], shared rides [49], and off-peak travels [44] are also observed through different types of gamified designs. Hence, the collective findings across these studies underscore the potential of gamification in promoting sustainable mobility especially in the urban context.

On the other hand, in the climate change resilience topics, studies address the vulnerability issues, resilience strategies, and adaptation behaviours in both urban and rural contexts, ranging from urban neighbourhoods and rural farming areas to cultural heritage sites and transboundary regions.

For the urban contexts, studies often focus on how gamified designs can simulate city-level sustainability and disaster preparedness. For example, in [63], players act as mayors to balance and harmonise choices while managing the budget, with results showing that the serious game effectively increased knowledge about risks and resilience among participants when facing temporary or long-term flooding and changes to coastal morphology in coastal areas. Another example ([75]) demonstrates the importance and effectiveness of gamification in engaging diverse stakeholders to collaboratively enhance neighbourhood resilience to climate issues. Vidou and Latinopoulos [75] leveraged the *Place Game* tool to engage urban residents, local business owners, and urban planners to co-create solution, being resilient at the neighbourhood level.

For the rural settings, the emphasis is often on local communities, and the gamified designs are used to simulate environmental risks like droughts, floods, and wildfires to raise awareness and engage participants for community solutions. For example, in the study [52], participants play web-based simulation games, and their behavioural changes such as crop choices and water usage are observed. This study focuses on community-wide solutions for groundwater conservation, and gamification plays an important role in understanding and influencing water use behaviours in this context, and it provides valuable insights into real-world challenges [52].

There is also a small number of studies that focused on other contexts, such as cultural heritage sites [53] or protected regions [64], which often focus on the issues of heritage preservation and environmental education.

3.3. Target users

A broad range of different users are targeted by scholars across the analysed studies, but in most cases without a clear characterisation of the main defining features of a group. Age is the most frequent demographic information mentioned, and it ranges from children (6–14) to adults (up to 67). Occasionally, income is addressed as in [27], where the focus of the study was on low-income communities in Bangkok. Interestingly, gender is rarely disaggregated, with [69] being the only one and comparing male-only and female-only gaming. Minorities are only occasionally represented, like in [74], where indigenous Bunun children are involved in the study. Fig. 4 shows the distribution of target users.

Citizens and residents are the most frequently targeted group, which reflects a strong emphasis on city-level and community-level engagement. Studies involving commuters include drivers, cyclists, and public transport users. Students at different educational levels (K–12, university, and postgraduate) are also a major focus, either due to the importance of youth involvement in climate risk mitigation and sustainable transport, or easy accessibility

There is a small number of studies that focus on policy makers, showcasing how gamification plays a role in the decision-making process and how it contributes to insights generation in sustainability planning. For example, in [73], serious games (i.e., *RAMSETE I, II, III*) are designed to engage policy makers, scientist, and private sectors, aiming to bridge the science–policy interface and foster mutual understanding. Another example is [65], where gamification (i.e., the game *AudaCITY*) is used to target city administrators and municipal staff involved in sustainability planning and governance. Here gamified solutions are helping them build capacity for long-term, integrated thinking and action.

Farmers and rural communities are less studied, but among these studies, most researchers focus only on land use, agricultural activities, and their resilience to climate change events, thus, the mobility is an overlooked theme. There are also some niche audiences such as tourists and professionals, which also demonstrate gamification's impact on

[2] Note: this number includes one study (i.e., [78]) that focused on a global level with data collected in both EU and other countries, and another study (i.e., [63]) that focused on an overseas territory of France in the Pacific.

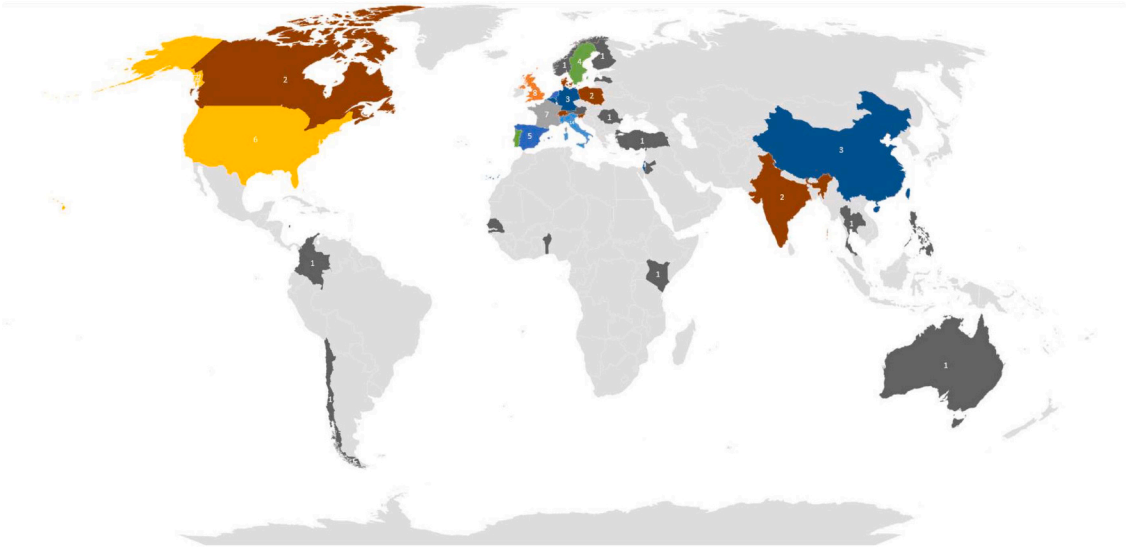

Fig. 3. Geographic distribution of the studies.

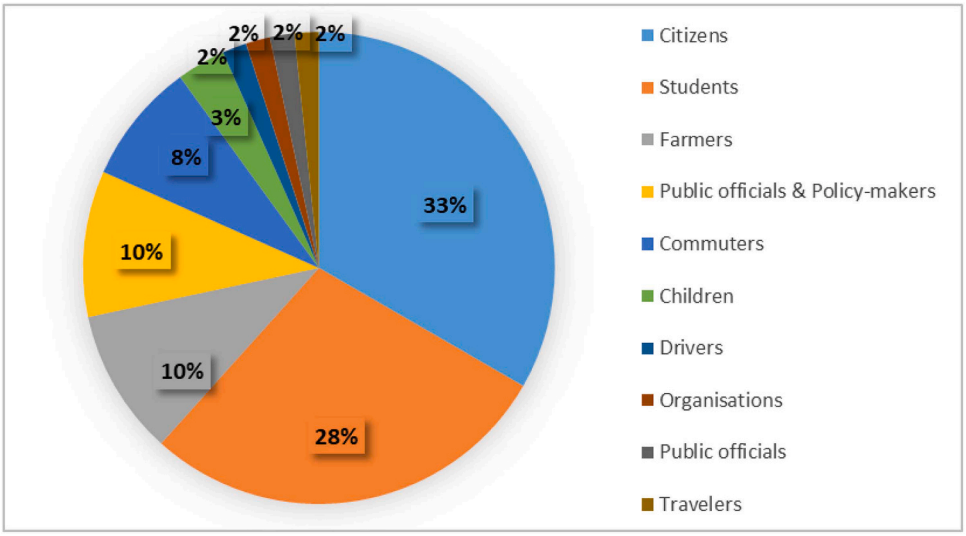

Fig. 4. Distribution of the target users.

specialised groups.

To sum up, in the domain of sustainable urban mobility and climate change resilience, gamification studies cover a wider range of target users, and these users are often easily accessible (e.g., university students, urban commuters, or general citizens) and their behaviours could be influenced. This reflects the sampling and logistical convenience in their empirical studies, but it also exposes a critical limitation, as underrepresented and marginalised communities, as well as older generations, are neglected.

3.4. Goal aimed

After the analysis of areas and target users, the review focuses on identifying the main reasons why gamification was considered as a strategic communication tool. With regards to sustainable urban mobility, gamification is first used for behavioural change and support sustainable transport systems. Specifically, active mobility (such as walking or cycling) is promoted via gamified interventions with a final aim of improving public health and well-being, while reducing traffic congestion and pollution [61]. Second, gamified apps and eco-feedback are used to promote public transport where citizens' mobility tracking is automatically recorded [34], and participants are persuaded to adopt sustainable transport modes. Last, the aim of using gamification can be linked to the need of reducing private vehicles on the road, addressing both local traffic problems and global environmental challenges [34]. For example, Olszewski et al. [36] used gamified carpooling system to reduce the number of cars and encourage shared commuting, and eventually, this behavioural change could improve traffic flow in the city and reduce carbon emissions, contributing to a low-carbon society [36].

In the climate change resilience context instead, gamification serves multiple strategic functions, including raising awareness, educating and engaging stakeholders, and supporting decision making. Specifically, gamification is effective in raising awareness about both general climate change and specific events risks. For example, Cook et al. [57] designed a humorous serious game to educate and build resilience against misinformation about general climate change, and Guido et al. [56] designed a web-based forecasting game app in response to the specific climate event – Monsoon rainfall, to increase climate literacy among citizens.

In this context, gamification is also used to involve diverse stakeholders in designing resilient urban spaces such as green infrastructure or placemaking. For example, Vidou and Latinopoulos [75] used the offline game *The Place Game* to engage local communities in evaluating and reimaging public spaces, empowering citizens to contribute to urban planning and climate resilience, hence, fostering collaboration and forming stronger social ties in the neighbourhood.

Last, gamification is also used to simulate historical and policy scenarios related to urban development and climate risk reduction (e.g., [66]), informing and supporting decision-making for policy makers and planners.

To sum up, the common goals of gamification in urban mobility are centred around awareness and behavioural change, while in climate change resilience, it aims not only at raising awareness, but also at planning and co-designing climate-adaptive public spaces, as well as informing policy and supporting decision making.

3.5. Measure of success

The effectiveness of gamified interventions hinges on how success is defined and measured. In the reviewed literature, most of the studies clearly defined success, often aligning with participants' behavioural change, engagement, and learning outcomes. For example, in the sustainable mobility context, Marroquín-Ciendua et al. [81] defined success as the likelihood of scooter use; Khoury et al. [60] defined success as a measurable shift of sustainable journeys before, during, and after the gamified intervention; and Khoshkangini et al. [31] defined success as the degree to which the personalised challenges in sustainable urban mobility are accepted and completed. In the climate change resilience context, Bell et al. [76] defined success as participants' shifts in preferences and perceptions in drought conditions; Heinzlef et al. [63] defined success as the increase in knowledge, awareness, and understanding of resilience and risk management; and Cook et al. [57] defined success as increase in resilience to misinformation and improvement in critical thinking and climate literacy. Among the reviewed studies, only a few papers did not define success explicitly, as they are conceptual frameworks or early-stages gamification proposals (e.g., [42,21]).

The measure of success varies across different studies. Most studies used mixed methods to strengthen their evaluation of the success of gamification. For sustainable mobility, Garcia et al. [68] used observational metric and post-game survey; Ferron et al. [35] used game logs, surveys, and interviews; Olszewski et al. [36] used multi-agent simulation, spatial data mining, and surveys; and Poslad et al. [39] used mobile app usage data and surveys. Similarly, for climate change resilience, Bontchev et al. [51] used surveys, interviews, and gameplay metrics (e.g., game scores, time played, hidden objects found, etc.); Vigna et al. [77] used observations, surveys, and interviews; Demaree et al. [52] used gameplay metrics and focus groups; Bruckermann [40] used ethnographic methods such as fieldwork, interviews, and participant observation. Survey is the primary tool used for measuring success, which is often paired with observations, focus groups, interviews, and simulated and mobile in-game data.

As for the success outcomes, most studies report positive results, indicating that success was achieved according to their defined metrics. Quantifiable results are most reported in the sustainable mobility studies, for example, Rogelj et al. [61] reported high motivation among participants and there was a 20.87 % increase in sustainable journeys during the gamified design; Di Dio et al. [37] reported positive user engagement in field test and there was an up to 65 % of CO_2 reduction in their best-case scenario. Although difficult to measure in concrete terms, also climate change resilience studies report some successful outcomes with most studies reporting qualitative outcomes such as enhanced learning through immediate feedback on decisions [50], increased stakeholder dialogues [77], and enhanced hazard recognition and improved decision-making processes [59].

4. Discussion

This review identified digital games as the most used type of game, European cities as the most considered area, and residents of the city as the most targeted demographic. Most studies share similar aims, as increasing active mobility and rising awareness of climate change, and altogether, gamification seems to bring positive results both in facilitating behavioural change and learning.

This section is now dedicated to discussing the main results of the performed review, and to highlight promising avenues for future research in the field.

4.1. Types of games and dynamics

Fig. 5 draws a timeline chart reflecting the evolution of gamification strategies by platform from 2009 to 2025. The temporal distribution of gamification reveals several overarching patterns in the literature.

As shown in the figure, first, digital platforms have consistently dominated the gamification landscape since 2009, with a notable surge from 2018 onwards, but the early digital games were primarily computer-based simulators, reflecting the technology limitations and research focus of the time, whereas from 2015 onward, there is a clear shift toward mobile applications, aligning with the global rise in smartphone adoption. It is worth noting that web-based and VR-based games began to appear more frequently after 2018, indicating a diversification of digital delivery media. However, such underrepresentation of VR-based games indicates a gap in empirical research, and this could be due to resource constraints or technological barriers.

Second, despite the digital surge, physical games, especially board games and role-playing games, have maintained a steady presence across the recent years. However, starting from 2014, it is interesting to see that hybrid approaches have gained attention, with a notable increase in and after 2021, and this could be due to the impact of COVID-19. These modes often combine digital simulations with in-person workshops or physical tools, which not only reflect the "new normal" after the pandemic, but also that gamification is evolving towards becoming a context-sensitive and inclusive intervention tool for learning and engagement.

Following, we detail the discussion for each game type and dynamics. As the review revealed that most of the work focuses on digital games, this allows researchers and users to tap into the increased availability of computational facilities, that can generate complex dynamics and realistic simulations. This class of games often leverages behavioural science (e.g., [55,30]) and data analytics (e.g., [38]) with real-time or delayed rewards to influence people's behaviours. In other areas, the possibility to leverage on complex dynamics and to provide rewards has already proved to affect behaviours and promote significant changes [90]. However, digital games do not lack crucial challenges that need to be considered. Their complexity and cognitively demand for the players [91], can lead to a reduced engagement or lack of adoption [92]. Further, digital games pose accessibility issues, as they require appropriate devices, services, as well as digital skills to be enjoyed [21]. Such issues are exacerbated in the context of VR games, and games that require continuous online access. In addition, computer-based games often are tailored to a specific social context, and this limits their generalisability and scalability. For example, Vigna et al. [77] tailored the game dynamics to the Italian Alps, hindering the expansion and application of this research to other contexts.

Physical games have been mostly explored in terms of board games and, to some extent, role-playing games. Interestingly, this review indicates that physical games mostly focus on climate change resilience topics. There is a missed opportunity to leverage on the well-established dynamics of physical games to explore solutions and educate users about sustainable mobility and related topics. This class of games tends to be effective because participants learn by doing, and tend to be involved in a friendly social context, that foster learning and exploration. Challenges

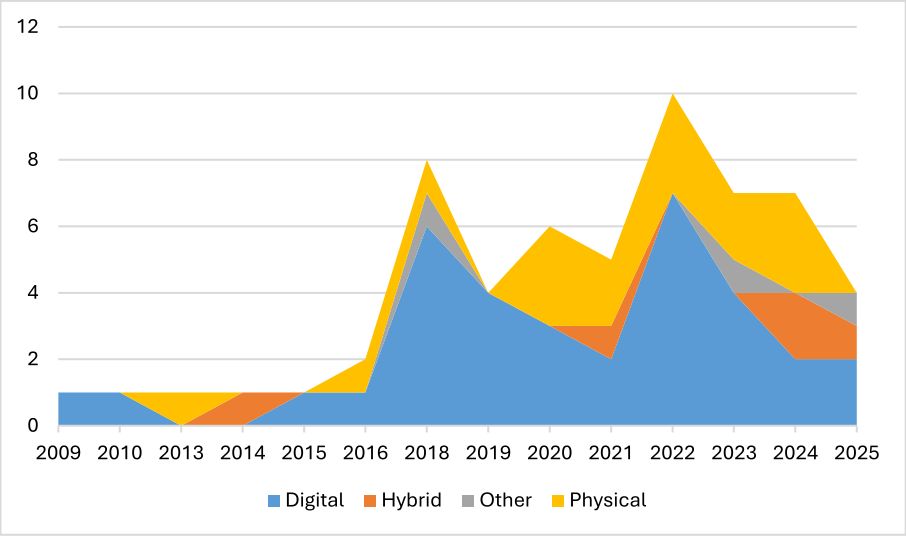

Fig. 5. Evolution of Gamification Strategies by Platform (2009–2025).

of physical games are the limited scalability and transferability into different areas or towards diverse problematics, and include psychological barriers due to a high need for abstract thinking and numeracy. Quiz-based games may also face cultural issues, particularly when they use humour or test "common knowledge". Further challenges that digital games do not pose, include the use of static and scenario-based that cannot support long-term engagement or help explore decisions consequences.

Researchers interested in adopting gamification in the context of sustainable mobility and climate resilience, could consider the following areas. The first interesting area to explore would be the enhancement of physical games by digital means, with the social aspects and well-established dynamics of the first benefitting from the ability of the latter to extend longevity and lead to long-lasting behavioural changes [79]. The boundaries between digital and physical games are becoming increasingly blurred [93,84], due to media convergence and increased accessibility of computing power. This trend, dubbed phygital [94], has been widely recognised from technological perspectives, and is increasingly implemented in market research [95]. There is however a limited exploration of the phygital space for sustainable transports and climate resilience gamified solutions, which could improve users gaming experience and could foster a more immersive engagement, and long-lasting behavioural change.

The second area that could be explored regards the implementation of Artificial Intelligence. This review identified a surprisingly underexplored research area, regarding digital games, that is the use of AI to tailor the gaming experience to the user or the context. AI has been extensively exploited in serious games [96] and has been proved effective in extending the longevity of games by e.g., adapting the storytelling to increasing engagement [97]. Longevity that seems to be one of the main issues of digital games in the context of sustainable mobility and climate change resilience, with users keen to start a new game but used to abandon it soon after [80].

Last, and regardless of the type of game implemented, researchers interested in investigating the use of gamification in the context of sustainable mobility and climate resilience will need to carefully consider the trade-off between potential and challenges if keen to use games. Pivotal in this case will be the aims of the desired gamification approach, and the target users and areas, keeping in mind that to generate a broader adoption, localisation, personalisation, and multilingual choices are strategically essential.

4.2. Incentives and measures of success

Incentives are a cornerstone of gamification approaches, as they prompt users' engagement and help retention. Even though many studies distinguish between intrinsic and extrinsic motivation, only a small number of research explicitly referenced conceptual or theoretical frameworks, such as self-determination theory (e.g., [35]), theory of planned behaviour (TPB) and technology acceptance model (TAM) (e.g., [30]), or theory of change (e.g., [71]). The use of formal conceptual frameworks is limited and fragmented in the reviewed literature, which highlights a gap in theoretical integration, and by adopting motivational theories, future research could enhance the rigour and replicability of incentives used in gamification. Below, we detail the discussion of incentives and measures of success.

A major decision when it comes to incentives regards the value of the reward offered: it must be perceived as fair and attainable, while being sustainable for the organisation that leverages the gamification approach. A delicate balance that deserves critical investigation and strategic planning. For instance, younger users may respond better to symbolic rewards, while older users may need more autonomy or relevance. Digital games are easier to use in this context as here rewards can potentially evolve and change over time to increase engagement and attractiveness. Beyond the value, the effectiveness of incentives depends on social norms and peer influence, and the right environment can amplify the effect and impact of incentives.

Moreover, from the review emerged that incentives are most effective when combined with education, social influence, and intrinsic motivators. In the context of peer groups and social communities, intrinsic incentives such as societal incentives can play a very important role, and lead to impact and results that are not easily achieved by other types of incentives and rewards [98].

Notably, rewards and extrinsic incentives may only have short-term effects if not paired with deeper engagement strategies. While incentives can be perceived as attractive in the initial interactions, they can quickly become ineffective in the long term. Most of the reviewed studies focus on a "snapshot" use of gamification approaches, and do not consider more long-term interactions. While this is understandable in a research context, the lack of longitudinal studies on gamified approaches in this field does not allow to deeply understand the long-term attractiveness of gamification, and to investigate techniques to maintain users interest maximising long lasting impact and behavioural change.

The measurement of success in gamification studies varies, depending on the research topics, field work contexts, and participants'

characteristics. Even though most of the studies clearly defined and measured success, the metrics and performance can vary, especially when surveys and statistical modelling are tailored to individual projects. Few studies employed validated scales such as the measurement from technology acceptance model (TAM) or theory of planned behaviour (TPB), but most of the studies relied on customised surveys or qualitative tools, which may raise concerns of the reliability and validity of the measurements. This suggests a need for standardised measurements, especially in similar research contexts, to encourage replicability. As mentioned above when discussing the effectiveness of incentives, also here a lack of longitudinal studies does not allow to measure the long-term impacts of the gamified design, as the immediate perceptual and behavioural changes may not best reflect the long-term effectiveness.

4.3. Areas of focus

The reviewed literature shows a wide range of geographic and social contexts. As presented in previous sections (Fig. 3), the strong representation of European regions in both urban mobility and climate change resilience research shows that European countries and cities are at the forefront of engaging in sustainable mobility and climate action. This could be due to a wide range of programmes and funded projects in Europe supporting such research, like England's *Green Infrastructure Framework*, Belgium's *Local Climate and Energy Pact*, the Netherlands' *Climate Adaptation City Deals*, and European Union's *Recovery and Resilience Facility* [99]. These programmes and projects are designed to enhance cities' ability to adapt to and recover from climate changes [99]. Due to the well-supported policy and funding in the European region, it is no surprise that researchers conduct their studies and collect data in these countries. Additionally, due to the dense and mature urban infrastructure, it provides an ideal context to study the mobility systems. From a practical point of view, these research findings serve as good examples for sustainable urban mobility transformation in cities as well as climate change resilience among citizens. However, this also highlights a geographic imbalance in research.

There is a lack of work focusing on the global south, as well as on developing countries. This can be problematic as climate changes and impacts are often more severe in developing economies, and here resources can be more limited. Further, challenges and issues vary significantly between different regions, areas, and climates. Hence, attempting to conduct research in most geographical area as possible would ensure to identify and devise all-encompassing impactful solutions.

While this review focused on academic research efforts, there are approaches that are not reflected in academic publications such as South Korea's *Bike to Work Challenge* [100] and Thailand's civic and environmental education games [101]. It is interesting to note that these approaches tend to be more common outside European regions, where existing pervasive applications for payments and social media interaction provide the ideal ground to include gamification aspects. Analysing the lasting effects of such application could provide novel insights for the field.

In sum, there is a geographic and demographic bias toward urban, European, and student populations in the existing literature, therefore, future research should aim to broaden representation and tailor gamification to diverse socio-cultural and infrastructural contexts.

4.4. Objectives and target user

Each study had a unique goal, yet it is possible to identify four main objectives shared across projects: behavioural change, education and awareness, stakeholder engagement, and policy support and simulation. These objectives align well with the gamification's nature as a strategic tool. The existing literature has leveraged different types of games to encourage shifts in mobility habits (e.g., 61, 30, 35); raise citizens and residents' knowledge and understanding of climate risks, sustainability, and resilience (e.g., 50, 63); facilitate participatory planning, co-creation, and collaboration among stakeholders (e.g., 21, 72); or model complex systems and test policy interventions in safe, simulated environments (e.g., 45, 67). Urban mobility studies tend to focus on behavioural change (e.g., modal shift, reduced emissions), while climate resilience studies emphasise more on education, awareness, and stakeholder engagement.

However, despite the identified patterns in the objectives, it is surprising to see that in the reviewed literature, the characteristics of the target users are usually ignored during the design of the gamified approaches. Existing work tends to focus on general categorisations such as "citizens" of a target urban area, or considers only demographics aspects such as income or minorities.

Part of the literature includes gamified tools in the attempt to co-design solutions by involving administrations, and various stakeholders. Interestingly, this appears mostly in climate change resilience studies. The lack of gamification for co-design solutions in the transport mobility context suggest an imbalance in responsibilities pending more towards the individual than the society as a whole. Further explorations of gamified solutions in this co-designing context could provide fresh insights.

The gender dimension is worryingly neglected, considered its importance in shaping how games are used and approached by different users [102,103]. This is particularly concerning when it comes to accessibility and inclusivity of gamification approaches for non-binary users [104].

In a similar fashion, demographics related to income and occupations are never explored in detail in the considered gamification approaches, but they do play a major role when it comes to the use of sustainable mobility services, or to the understanding and supporting of climate resilience measures [105]. Further, there is a lack of consideration for the level of education of the target users, that again plays a major role in characterising the attitude of people towards the topics of climate change and of sustainable mobility.

It is also worth noting that, when it comes to age cohorts, elder users are never targeted in gamification approaches. On the one hand, this can be justified in terms of accessibility of these approaches for elder citizens; on the other hand, this decision is excluding a growing percentage of urban populations, that consistently uses and needs mobility services in urban areas [106].

In conclusion, a gamification strategy contains multifaceted game elements and there is no one-size-fits-all solution or design that can be deemed the most effective in all contexts, yet. To influence real-world behaviours of different target users, the literature demonstrates that gamification is a powerful tool, but the specific game elements can vary based on demographic and sociographic factors, and need further investigation

5. Conclusions

This study systematically reviewed gamification approaches in the areas of sustainable urban mobility and climate change resilience, to foster a synergistic combination of these two intrinsically linked aspects of sustainability. As a first major outcome, this review highlights the lack of work considering both aspects together in a gamification framework. This is a significant missed opportunity, considering the deep link between the two aspects. Particularly, it would be beneficial to explore approaches where sustainable urban mobility and transport resilience are merged: from a behavioural perspective, these two elements are very closed together and can be easily included in a holistic gamification approach. This has the potential to influence citizens behaviour and to increase awareness of the importance of a resilient transport system – a critical aspect of any climate-resilient society [107].

An interesting gamification dynamic to leverage upon in this context is the community building. Gamification often incorporates social elements, allowing users to compete with friends, join teams, or contribute

to collective goals. When incorporated into approaches that consider both sustainable mobility and climate resilience, this can foster a sense of community and normalise sustainable and resilient behaviours, as people are more likely to adopt practices they see others embracing [108]. Further, it could foster healthy competitions between different communities, and support the emergence of sustainable communities [109]: local communities could strive to excel in improving the resilience of their local area, and to demonstrate their wide adoption of sustainable transport.

More in general, our review highlights that in the separate areas, gamification has been widely adopted as an effective strategy to enhance user engagement, motivation, and learning outcomes. The diverse range of gamification elements, such as media, incentives, and narrative, and in their various combinations have led to some positive influence of user behaviour and performance. Yet, despite the promising results, several challenges remain. The review underscores the need for more rigorous empirical studies to establish the long-term impact of gamification. Additionally, there is a need for standardised frameworks and guidelines to assist practitioners in designing and evaluating gamified systems, as well as the need for a less Europe-centric focus of the studies.

Future research should focus on leveraging the synergies between sustainable mobility and climate resilience, exploring the potential of artificial intelligence in supporting the engagement of users, and in improving the geographical distribution of studies as well as the attention to the needs of different target users.

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CRediT authorship contribution statement

Qi Zhang: Writing – original draft, Methodology, Investigation, Data curation. **Alessia Grassi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Mauro Vallati:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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