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SILENT SPREAD: USING A DIGITAL SERIOUS GAME ON *PHYTOPHTHORA CINNAMOMI* TO FACILITATE COGNITIVE THINKING PROCESSES AND INSPIRE THE CREATION OF A COGNITIVE SUSTAINABILITY COMPASS

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Certification

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List of Abbreviations

BCD - Bloom's Cognitive Domains

KA – Knowledge acquisition

IPM – Integrated Pest Management

Pc – *Phytophthora cinnamomi*

SGs – Serious games

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Abstract

Serious games (SGs), or games that are valued for educational utility rather than pure entertainment, has grown exponentially in academic research. In agroforestry, SGs is at an impasse. This is a missed opportunity to tackle the difficulty in teaching complex biological processes, and the costly training of courses such as pest management and sustainability. Integrating SGs into pest problems and sustainability is not straightforward due to the lack of structured guidance in assessing outcomes such as knowledge acquisition (KA). The need to examine the game elements that are effective in facilitating KA persists as a subject of debate with little empirical evidences to date. This study explores the utilisation of SGs in fostering KA about *Phytophthora cinnamomi* (Pc), an invasive soil-borne pathogen threatening Mediterranean oak ecosystem in Spain. Building on Bloom's Cognitive Taxonomy as framework, the research aims to evaluate which specific game elements (trivia, quiz, in-game management, game events) facilitate the five cognitive thinking processes, and whether SGs can serve as effective tools to inspire sustainability reflections post-gameplay through the use of Cognitive Sustainability Compass. Silent Spread, a digital board game, was developed and played by 35 university-level students. Using Partial Least Squares Structural Equation Modelling, empirical data shows that in-game management acts as the main game element driver, displaying significant associations in facilitating cognitive thinking processes such as applying, analysing, and evaluating. PLS-SEM demonstrates that Silent Spread fostered middle- to higher-order thinking skills, wherein analysing served as the strongest mediator in teaching spread mechanism. Meanwhile, the Cognitive Sustainability Compass session reveals that social sustainability pillar was the most frequently cited, emphasising key themes such as collaborative experiential learning and feeling more connected to rural realities post-game. The study highlights that given the strong facilitation of knowledge application rather than basic factual recall and surface level comprehension, SG research should start examining how SGs can teach learners to apply their knowledge within and outside the limits of virtual games. Furthermore, the research challenges the lens of Bloom's hierarchical progression of KA, stressing that the 21st century requires 21st century skills such as collaborative problem-solving and systems thinking that players successfully manifested. Overall, Silent Spread presents a promising tool to train future rural development professionals, policymakers, forest engineers, and farmers who are future proof, capable of navigating complexities in agroecology and sustainability transitions.

Keywords: sustainability education, game-based learning, agroforestry, Bloom's Taxonomy, invasive species

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What do digital games, invasive root pathogens,
and Iberian pigs have in common?

1. INTRODUCTION

Agroforestry integrates disciplines from agriculture, forestry economics, and social sciences (Rudebjer et al., 2001). The discipline describes two characteristics that separates the practice from other land uses. The approach “deliberately grows woody perennials on the same unit of land as agricultural crops and or animals, either in some form of spatial mixture or sequence” (Nair et al., 2021, p.22). The heterogenous habitats the system generates improve ecological resilience (Jose, 2009), sequester carbon (Albrecht & Kandji, 2003), and reduce farmers’ vulnerability to market and climate shocks (Garrity, 2004). These benefits, however, are contingent upon contextually appropriate design, species selection, and long-term upkeep (Mbow et al., 2014). Without proper planning and ongoing management, agroforestry systems risk falling short of their potential or even lead to unintended negative outcomes (Schoeneberger et al., 2012).

To fully maximise the benefits agroforestry provides, forestry has begun to pioneer didactic innovations and pedagogical methodologies (Villarraga-Florez et al., 2016). Forest teaching permeates from primary to tertiary levels, and can be formal and non-formal (Gabay & Rekola, 2019). However, curating effective educational programmes remains a formidable undertaking. Discussion on making forest education more effective and appealing to a broader public to meet contemporary society remains a long-standing debate (Rodríguez-Piñeros et al., 2020). The challenges can be defined within two principal contexts, namely a) agroecology's inherent complexity, interrelatedness, and globalised perspective, and b) overlook on tailored topics in agroforestry in emerging educational tools. Firstly, trainings in agroforest approaches, like agroecology (De Graeuwe et al., 2024), is rendered arduous by the intricate complex biological processes, landscape interrelatedness, and the globalised nature of the system. In Europe, agriculture programs are rarely imbued with interdisciplinary methods (Francis et al., 2008). This pedagogical lacuna leaves university students insufficiently prepared with systemic perspectives, disabling their abilities to connect complex relationships (Francis et al., 2011) and tackle sustainability-related issues. It is thus imperative to curate interdisciplinary pedagogies for teaching agroecology that encapsulate and critically integrate economic, social, and environmental dimensions (Francis et al., 2019).

The second analytical lens focuses on emergent pedagogical innovations. Instructional materials like **serious games (SGs)** have been identified (Duru et al., 2015) as promising tool of addressing persistent educational deficiencies across multiple sustainability domains. SGs refer to "games that do not have entertainment, enjoyment or fun as their primary purpose" (Michael & Chen, 2006, p.21). Within agriculture, however, most applications remain confined to analogue board games (Dernat et al., 2019). This constitutes a salient limitation, insofar as physically formatted games impede international accessibility and constrain interactivity; two widely acknowledged factors for effective learning facilitation (Vogel et al., 2006). Given the digital SG-research in agroforestry remains in its nascent stages, the majority of extant examples continue to focus on crop or animal production (Calsamiglia et al., 2020; Dourmand et al., 2016). Such a lacuna has resulted in critical themes, such as pest management, being systematically overlooked. Taken together, a) the difficulty in holistic learning in agroforestry, b) the lack of digital SG to facilitate international access, and c) the limits to how far SG can explore agroforestry management shape the general research question: can serious games be used in teaching university-level students agroforest practices like pest management?

1.1 Serious games

Several concepts are associated with SGs, overlapping with terms such as e-learning, edutainment, game-based learning, mobile learning, and digital game-based learning (Susi et al., 2007). Despite the confounding definitions that exist, SGs are generally framed as a tool designed to be engaging and motivational (Susi et al., 2007). These two dimensions are pivotal in skills and abilities development. Thus, following the definition of Susi et al. (2007), SG is contextualised in this research as "games that engage the user, and contribute to the achievement of a defined purpose such as education and learning, other than pure entertainment". The efficacy of SGs to simplify complex real-world systems into a more tangible presentation of information offers a promising tool in sustainable transformation research (Foppe & von Wehrden, 2024), agricultural innovation (Dernat et al., 2025), and ultimately, knowledge transfer across domains (Ullah et al., 2022; Zhoggen et al., 2019).

SGs as a research method is by no means novel. The concept has long been used in economic inquiry such as the Prisoner's Dilemma (Axelrod, 1980) and the Ultimatum Game (Bolton & Ockenfels, 2000). SGs have also garnered prominence within the social sciences, mainly in behavioural differences research (Liu et al., 2022; Sarin & Wieland, 2016) and sustainability policy (Czaika & Selin, 2017). The method's focus covers transformation systems through analogue games (Salvini et al., 2016), digital video games (Espinosa-Curiel & de Alba-Chavez, 2024) and hybrid formats (Martin, 2015). While each mode has its own advantages, online digital games' salient features in terms of flexibility (Morgan et al., 2024) warrant particular emphasis. Firstly, online games can define and control the environments that draw inspirations from real-world contexts and pressing social problems. Secondly, these games can reach participants and stakeholders globally; an audience reach that analogue games cannot perform. Lastly, the embedded features of digital games permit the testing of multiple hypotheses, a capacity that is particularly consequential for the nascent development of agroforestry as a scholarly discipline. For instance, time pressures can examine dynamic data such as learning rates and how experiences shape decision-making (Carusso et al., 2008; Merril et al., 2019). The accelerated growth of digital mobile games during the COVID-19 pandemic (Atwood-Baline & Huffman, 2017) positioned the tool as a movement with immense application in education, training and instruction (Connolly et al., 2012). Since games facilitate a 'learning by doing' approach (Fernandez Galeote & Hamari, 2021), SG's capacity to render complex systems and global challenges in sustainability, agriculture, and agroforestry more tangible and socially relevant is particularly compelling.

1.2 Digital Serious Games and Sustainability

Sustainability emerges from the attempt to integrate a wide range of environmental issues pinned with socio-economic challenges (Hopwood, Mellor, & O'Brien, 2005). Provided that sustainability and sustainable development knowledge can no longer be overlooked (Stanitsas, Kirytopoulus & Vareilles, 2019), new teaching methods require revisiting and refinement (Dagiliute et al., 2018; Jaca et al., 2018), however, doing is far from straightforward. Learning sustainability presents complexities owing to its prevailing interdisciplinary nature, such as in fields like ecology, economics, politics and culture (dos Santos, Strada & Bottino, 2019). The case-specific challenges, complex system dynamics, multiple worldviews, and overlapping stakeholder framings make sustainability education extremely difficult to address comprehensively. Nonetheless, tackling the task is by no means trivial since the three tightly coupled pillars of sustainability are have achieved normative acceptance within the research community, providing a concrete analytical foundation. Adopting Harris (2003)'s definition and the study of dos Santos, Strada & Bottino (2019), these pillars include:

> a) "***Economic sustainability***: the ability to maintain an adequate and continuous production of goods and services with manageable levels of government and external debt;
> *b)* ***Environmental sustainability***: the ability to maintain adequate levels of renewable resource harvesting, pollution production and depletion of non-renewable resources;
> *c)* ***Social sustainability***: the ability of a social system to provide "social well-being", characterised by equal access to and delivery of basic facilities and social services, equal opportunities and political accountability and participation."

SGs that address sustainability evince a promising trajectory in sustainability education (Stanitsas, Kirytopoulus & Vareilles, 2019). The discernible upward trend highlights the potentials of novel instructional materials and knowledge-transfer mechanisms that present prominent roles in SG development (Stanitsas, Kirytopoulus & Vareilles, 2019). However, while SG's contribution and efficacy in knowledge contribution is demonstrable and conclusive, empirical evidence regarding their capacity to holistically shape participant's sustainability values require more attention (Katsaliaki & Mustafee, 2015). Findings show that the theoretical background of SG is "not enough to engage students in a holistic approach to the philosophy of sustainability" (Stanitsas, Kirytopoulus & Vareilles, 2019, p. 930), a rather veritable Achilles' heel of contemporary pedagogy. Notably, there is an urgent need for more evidence-based research in sustainability-centred SG, concretising immediate pathways to explore changes in learner's knowledge to specific sustainability problems (Strada et al., 2023; Diniz dos Santos et al., 2019; Janakiraman et al., 2018), and integrate multiple measures using both in-game learning analytics and out-of-game assessments (dos Santos et al., 2019; de Haan & van der Voort, 2018; Strada et al., 2023;). Provided that sustainability is ubiquitous in many environmental issues such as water management, ecosystem ecology, and environmental education, there remains niches that warrant more empirical explorations like agriculture and silvopasture management (Madani, Pierce & Mirchi, 2017).

1.3 Digital Serious Games in Agriculture

Earlier explorations of digital SGs encompassed innovations in agroecology (Jouan et al., 2021), livestock farming (Calsamiglia et al., 2020), and environmental education (Khelifa & Mahdjoub, 2021). These environmentally oriented games reflect the observed trend in SGs' evolution. Earlier digital games were originally lean towards education and economic issues with a now evolving paradigm moving towards environmental stewardship with social themes (Dernat et al., 2025).

In agriculture, SGs address sustainability challenges through complex scenarios. A corpus study conducted by Dernat et al. (2025) highlighted the farmers' practices as one of the two core focuses in SGs historical development alongside global sustainability. Yet, despite the salient emphasis on sustainable farming approaches in SG scholarship, several domains remain comparatively underexplored. For instance, there is a growing interest in market gardening, arboriculture, viticulture, and pest management in game development (Boulestreau et al., 2023; Rouault et al., 2020; de la Vega et al., 2022). The latter is of particular importance, as "pests are often invasive species" readily introduced by the general public as inadvertent vectors (de la Vega et al., 2022). This strengthens the need to engage various sectors, particularly future forest managers, to impede the proliferation of pests in various ecosystems.

Teaching pest management, even to students outside agricultural disciplines, is of particular importance. In industrialised economies, people are disconnected from various means of managing pests (Sutherland et al., 2020); all the more reason to develop educational tools to increase awareness (Helmberger et al., 2022) across geographical and education system boundaries. Additionally, concepts such as integrated pest management (IPM) are complex and deeply rooted in ecology and economics that can be difficult to grasp (Helmberger et al., 2022). This is where digital SGs can present as a viable solution. Learning mechanisms such as 'learning by doing' (Fernández Galeote & Hamari 2021), and peer interactions during play (da Silva Júnior et al. 2020; Nadolski et al., 2008) enhance student's learning outcomes (Cheng & Annetta, 2012). Two notable digital SGs centred on pest practices exist, namely Pest Quest (Helmberger et al., 2022) and Spotted-Stop-It (de la Vega et al., 2022). The games exemplified how transmitting concepts and practices can be learned where game concepts become effective tools. However, given the vast array of pests that can inspire digital games, there still remains considerable scope for future empirical investigation. Building on this foundation, this research aims to contextualise SG development using *Phytophthora cinnamomi (Pc) as* the empirical context.

1.4 Game Development

Before diving into the contextualisation of *Pc* into SG, it is imperative to first delineate the broader concept of game development. Creating video games is an iterative process, however, a generic sequence common in developing instructional and training materials follow five phases termed as ADDIE model. The process involves a) Analysis, b) Design, c) Development, d) Implementation and e) Evaluation (Yusoff & Shafiril, 2019). Analysis involves clarifying the instructional problem, goals, and objectives. The Design phase encompasses the specification of learning objectives, instructional exercises, content, subject themes and even media selection (Yusoff & Shafiril, 2019). The development stage begins with developers creating and assembling the content assets where a test stage is often implemented to assess whether the game behaves the intended tasks. Implementation deals with the development of protocols, further ensuring the any error or bugs are absent. Lastly, the evaluation phase is comprised of testing the project with users to improve further specifications (Yusoff & Shafiril, 2019).

1.5 *Phytophthora cinnamomi* as the Empirical Case Study

Pc is widely recognised for its devastating effects on plants (Hardham & Blackman, 2018) (Figure 1). With over 5 000 host species, contamination most commonly occurs through nursery stock, plant material, food crops, and native forests (Hardham, 2005). The pathogen can survive in the soil by living off dead organic matter. It remains in the soil or in infected plants as tough resting structures called chlamydospores, and sometimes as oospores (Weste, 1983; Zentmyer & Mircetich, 1966). When conditions like moisture and temperature are right, the pathogen becomes active and starts reproducing asexually. Once inside a vulnerable plant, the pathogen can produce more sporangia on the plant's surface within just 2 or 3 days. This asexual cycle can happen repeatedly in a short time, quickly increasing the number of infectious particles in the area. Pc can survive in most soil for up to 6 years and moisture is one of the key factors that establishes the Pc-related diseases (Hardham, 2005).

Pc as an invasive root pathogen, has been documented in no fewer than 15 of the global biodiversity hotspots (Myers et al., 2000) (Figure 2). In Europe, Pc impacts chestnut and holm oak forests (Serrazina et al., 2015). In Mediterranean countries like Spain, the pathogen is regarded as a major threat to economically vital species like holm oaks (*Quercus ilex*) and cork oak (*Quercus suber*). More than 8 000 ha per year were estimated to have been affected by holm oak loss in Spain in 2010 (Senado, 2010) and around 30 000 ha in the Iberian Peninsula was devastated by *Pc* from 1957-2013 (Beatriz et al., 2024). The weakening sites where oak decline has been observed infect open woodlands known as 'dehesa'. Such tree mortality rates are critical because Dehesa ecosystems consider trees as ecosystem engineers. They primarily "maintain grass production in poor soils under a semiarid climate" (Moreno & Pulido, 2009, p. 2).

Additionally, the effects on the sustainability of these ecosystems are even amplified due to the confluence of factors like intensification of agricultural practices (Sales-Baptista et al., 2016), lack of regeneration of trees (Moreno & Pulido, 2008), and direct effects of climate change (Gil-Pelegrín et al., 2018). With the ongoing threats of *Pc* for the last three decades, to the author's knowledge, there has been no exploration of SG, be it analogue or digital format, where the pathogen served as the main game inspiration.

1.6 Contextualising *Phytophthora cinnamomi* in Digital Serious Game Development

Three factors make *Pc* a compelling case for the creation of a digital SG. These can be summarised into real-world relevance, complex ecological impacts, and pedagogical potential. The multi-faceted approach to early detection and containment management makes *Pc* an ideal subject for an interactive and immersive game. Additionally, the significant threat to biodiversity and forest ecosystems worldwide (Hardham, 2005) (Figure 2) heightens the urgency to develop educational materials to inform the public and train future forestry professionals. At a regional level, cumulative results of leading scholars in *Pc* illustrate the current and projected potential distribution in Andalucia, Spain (Duque-Lazo et al., 2018) (Figure 3). Moreover, while several biological concepts can be embedded in the game (e.g. life cycle), challenging players to make strategic decisions facilitates an experiential learning as opposed to a typical classroom setting. Concepts like disease transmission, tree health monitoring, and biosecurity protocols (Marzano et al., 2017) can add to game-setting, mirroring real-life tasks in *Pc* management. This aligns with the principles of effective SG design, which emphasise relevance, quick feedback, and calibrated challenge to enhance motivation and learning outcomes (Sitzmann, 2011). Overall, integrating *Pc* into digital SGs supports the need for more educational materials for the public while simultaneously offering an interactive, and real-life based learning opportunity. Unlike most existing games not emphasising the real-world processes in forest and pest management, this exploration underscores both a timely gap and a worthwhile scientific endeavour. The study attempts to bridge the methodological and empirical gap positioning *Pc* in digital SGs development. This area remains scarcely studied in the coupled game and pest management research.

Figure 1. Microscopic image of Pc.
Source: Robin, Smith & Hansen (2012).

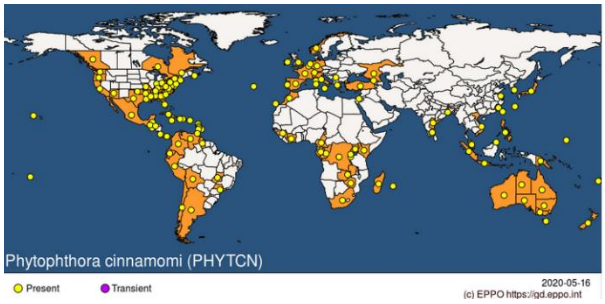


Figure 2. Global distribution of areas where Pc has been identified. Source: de Andrade, Branco & Choupina (2020).

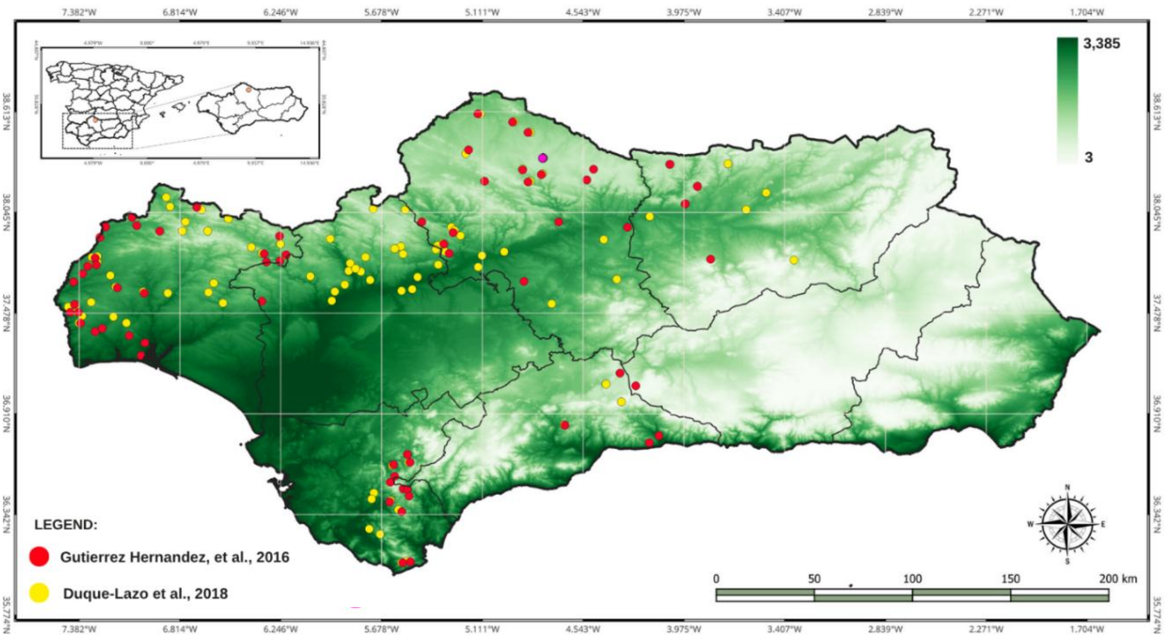


Figure 3. Distribution map of Pc in Andalucia, Spain. Note: The green gradient represents the topography in the region. Source: Duque-Lazo et al., 2018; Guiterrez Hernandez et al., 2016. Processed by: Darapisa, 2025 Processor: QGIS

2. REVIEW OF RELATED LITERATURE

SG development has grown at an exponential pace in the video games market (Alvarez & Michaud, 2008) and in academic research (Ritterfeld et al., 2009). Between 2000-2020, the trajectory of SG research increasingly converged with themes such as natural resource management, conservation, ecology and agricultural sustainability (Hernandez-Aguilera et al., 2020). SGs, despite being recognised as a "game-changer for learning, increasing coordination, and supporting decision-making in sustainability transitions" (Dernat et al., 2025, p. 1), the innovative research tool still presents vast research opportunities that demand further empirical substantiation and contextual refinement.

For specificity and clarity, the research follows a rather an unconventional approach wherein the identified gaps through review of related literature were discussed first in order to comprehensively present the research problems. An organised summary of earlier studies on the use of SG in forestry, tree health, and pest management is explored in the section, enabling the understanding of the general landscape of SG research in forestry. The comparison of the studies uses multi-component analysis (n=15) focusing on the game elements and mechanics that enhanced learning or hindered its facilitation (Annex A-D). This analytical step subsequently informs the formulation of the research questions and the operationalisation of the variables that underpin the structural model quantitatively examined in the study.

2.1 Serious Games for Knowledge Acquisition: The Identified Theoretical Application Gap

There are substantial corpus of studies claiming the positive outcomes of games (Connolly et al., 2012) yet the scholarly consensus remains tenuous, lacking coherence (Ke, 2009) and persistently fragmented (Connolly et al., 2012). For conceptual consistency, impacts and outcomes are defined as the inclusion of "'softer' emotional, motivational and attitudinal outcome as well as 'harder' knowledge acquisition and skills" (Connolly et al., 2012, p. 662). Some authors argue that gameplay enables participants to perform more effectively than under controlled conditions (Arnab et al., 2013; Suh, Kim & Kim, 2010) while others demonstrated computer-based simulations can be equally efficacious as conventional classroom instruction (Rondon, Sassi & de Andrade, 2013; Nishikawa & Jaeger, 2011). These confounding results can be justified by the differences in the type of SGs being used (e.g. board game, simulations, 3D, 2D interfaces), the subject field applied (e.g. politics, health) and the learning outcome being assessed (e.g. practical, theoretical knowledge). Without the proper evaluation of how games foster the intended knowledge and skills (O'Neil et al., 2013) and the impact of playing to understand what works in the game (O'Neil et al., 2013), game environments can be unmotivating. Hence, standardising SG evaluations is paramount with sufficient latitude for contextual adaptation.

2.1.2 Knowledge Acquisition

Measuring success and what success entails in game evaluation is hard to assess (Maharaj & Green, 2015). Success may be defined in terms of the quantification of the number of downloads, the amount of time spent playing the game, the knowledge acquired, or the behavioural changes the game provided among others. Impacts such as **knowledge acquisition (KA),** physiological and perceptual, and cognitive outcomes were among the common results from playing games (Boyle et al., 2016). KA remains the most frequently occurring outcome among games designed for learning (or games for learning). Connolly et al.

(2012) supported this claim placing KA or content understanding, alongside affective and motivational outcomes as the central themes in impact valuation. In a surface level, KA being a commonly recurring theme inevitably provokes the question of why this particularly outcome emerges as the common denominator across evaluation studies. Concentrating on KA alone, despite other widely studied impacts co-existing, presents a plethora of research opportunities and underexplored domains. These windows of exploration include investigating the transferability of acquired knowledge to real-world contexts (Mayer, 2019; Qian & Clark, 2016) by examining which game element contribute meaningfully in knowledge absorption. Similarly, another research arena can dive deeper on the analysis of cognitive processes as mediator of KA (e.g. lower order thinking, higher order thinking skills) (i.e. Anderson & Krathwohl, 2001; Bloom; 1956), which can be analysed during and post-gameplay. Exploring further these cognitive processes constitutes a fruitful scholarly endeavour, as theoretically-grounded SGs require intentional injection of learning content, pedagogical approaches, and ultimately theories that can add depth to learning outcomes (Plass, Homer & Kinzer, 2020).

2.1.3 Bloom's Taxonomy of Educational Objectives

A familiar tool among educators is Bloom's Taxonomy of Educational Objectives (1956) (Figure 4). The framework is referred to interchangeably with terminologies such as Bloom's Taxonomy, Bloom's Cognitive Taxonomy, and Bloom's Cognitive Domains (BCD). The six-level taxonomy is a hierarchial classification of cognitive thinking processes that educators set as learning objectives (Krathwohl, 2017; Buchanan, Wolanczyk & Zinghini, 2011;). BCD provides the structured framework to achieve such objectives. Educators use BCD to "specify objectives to plan learning experiences and prepare evaluation devices" (Bloom, 1956, p.2).

The original taxonomy comprised six categories, namely Knowledge, Comprehension, Application, Analysis, Synthesis and Evaluation. In 2001, the hierarchy was revised by Bloom's former students which includes Remember, Understand, Apply, Analyse, Evaluate, and Create. The revised taxonomy aims to provide flexibility and alignment with how people actually learn and think (Anderson & Krathwohl, 2001). These revisions are often viewed twofold which tackle cognitive process (usually the verb, e.g. understanding, applying, etc.) and the knowledge type (noun, e.g. factual knowledge, procedural knowledge). To provide clarity on cognitive thinking processes, the terms were defined below following Anderson & Krathwohl (2001) iterations:

(a) Remembering. The hierarchy refers to the ability to recall facts, definitions, or basic concepts from memory. It represents the foundational level of cognitive learning, focusing on recognition and retrieval of previously learned information.

(b) Understanding. The thinking skill involves grasping the meaning of information by interpreting, summarizing, or explaining ideas in one's own words. It goes beyond memorization, showing comprehension of concepts and relationships.

(c) Applying. This refers to the use of knowledge in new situations or contexts. Learners demonstrate this level by solving problems, carrying out procedures, or using information in real-world scenarios.

(d) Analysing. Analysing involves breaking down information into components to understand its structure, relationships, or underlying logic. This level includes comparing, contrasting, and examining patterns or cause-and-effect connections.

(e) Evaluating. This thinking skill refers to the ability to make judgments based on criteria and standards. It includes critiquing, defending opinions, and assessing the value or credibility of information or methods.

(f) Creating. The process entails putting together elements to create a new, coherent, and functional entity based on certain rules and categories.

Hereafter the six cognitive thinking processes described earlier (Figure 4) will be referred interchangeably as cognitive levels, cognitive hierarchies, and cognitive thinking skills. The taxonomy can help teachers design evaluation devices and plan learning experiences. The framework extends beyond simple recall by fostering knowledge application in context, such as analysing the conditions under which knowledge is mobilised. Thus, BCD presents a robust theoretical underpinning that stresses the levels of cognitive process, an investigation often overlooked despite KA appearing in many SG-evaluation studies.

The use of BCD in assessing thinking processes has been widely explored (e.g. Eber, 2007; Lemons & Lemons, 2017; Ullah, et al., 2019; Semsar & Casagrand, 2017;), albeit not necessarily heavily contextualised in SG. The prospects of embedding BCD are particularly promising because KA is more readily observable, quantifiable, and explicitly aligned with defined learning objectives (Shute & Ventura, 2023). For instance, learned knowledge can be easily assessed after game-play as compared to other outcomes like how behavioural impacts take time to manifest. Such quick evaluation post-game is important for educational and training contexts where the processing of targeted concepts defines the primary aim (Gee, 2003).

Figure 4. Bloom's Taxonomy of Educational Objectives (Bloom, 1956)
Note: Author's own visualisation of the taxonomy.
Source: Information Technology, University of Florida, n.d

BCD integration is not inherently difficult; however, it might be easier said than done, particularly in assessing the highest level, creating. Games are typically designed to engage players with certain rules and mechanics. Embedding assessments that capture "creating" may entail additional rules that may conflict with the gameplay flow, hence, adding complexity to the game which is strictly avoided in game design (Waeber et al., 2023). Additionally, the essence of the thinking hierarchy entails creating a new concept that may not necessarily be applicable within the game but possibly outside the game. One might argue that combining strategies constitutes "creating"; however, the skill properly entails demonstrating knowledge transfer to different contexts. In-game evaluators, whether automated scoring systems or human assessors, may struggle to capture the subtle nuances of genuine creativity and innovation.

While the reasons outlined above is purely a personal choice based on earlier understanding about game developments, it is worth emphasising that supporting literature on this challenge remains sparse. Shute & Rahimi (2021) mentioned that "more work is needed in the area of automated assessment of creativity" (p. 11), particularly in fields like learning sciences, psychometrics, and creativity studies. Moreover, there is an inherent disconnect between playing games and creativity (Shute & Rahimi, 2011). Earlier discussion claims that playing games do not significantly increase Torrance Tests of Creative Thinking (Hamlen, 2009) while some put forwarded that in fact, spending considerable time playing game is significantly associated with creativity (Jackson et al., 2012). Investigating the relationships of creativity and gameplay does not necessarily translate to educators adopting SGs as creativity facilitator tool (Shute & Rahimi, 2021). This notion hinders the further exploration of the creativity-SG merging, but notably, still, a worthwhile endeavour. Studies show that people need to engage with the basic learning requirements of the domain before creativity spark (Baer & Kaufman, 2005). Moreover, creativity lies at the intersection of the person, a domain and the field experts (Csiszenymihalyi, 1997).

Several game evaluations widely adopted theoretical underpinnings in cognitive science, the study of how humans think and learn in a given condition (Bruer, 1993). The cognitive studies lens as an agent encourages a more detailed analysis of KA, which can be discussed twofold. Firstly, any changes in the environment can create information and knowledge (Nonaka, 1994). SGs being used for educational purposes is an abrupt change from classroom settings to virtual environments. This shift necessitates a comprehensive analysis of how students process information driven by digital surroundings and inputs. Secondly, digital communication moved away from simply acquiring knowledge but of its usage (Sarrazin & Sikes, 2013). In general, people are considerably poor in understanding information or may take time to process and use it (Barsalou, 1999). Games can put information in a controlled environment where players can slowly navigate through. Consequently, there is a need for an in-depth exploration how controlled environments rich with information can facilitate learning.

Overall, capturing the cognitive dimension of learning can be an effective tool for long-term change and application of concepts (Gee, 2003); two components that educational learning materials need to impart to their learners. Despite being extensively researched, exploring KA further is a worthwhile endeavour due to (a) being readily observable post-game, and (b) its anchor to cognitive science. Existing studies only evaluated the outcome of games as a whole without digesting the different cognitive processes of knowledge SGs have impacted. This research argues that this could be explained by the lack of theoretical operationalisation that can systematically internalise the different knowledge learned, leading to the theoretical application gap of the current study.

2.2 The Theoretical Application Gap of the Study

The majority of the research organised in the study (Annex A) did not explicitly articulate how leading theories inform game features and the levels of KA obtained by the players. An exception to this generalisation is the research of Yusoffa & Shafiril (2019) which discussed how behaviourism, constructivism and social learning shape the pedagogical outcomes of their instructional materials. Moreover, whenever outcomes are investigated, oftentimes there are three dimensions being compared (e.g. cognitive, incentive, and interaction) (Cosme & Turchen, 2020). This approach is not inherently problematic, rather a missed opportunity to undertake a more nuanced and systematic inquiry of the different levels of KA. To reiterate, this research argues that even if KA keeps on recurring as a primary outcome of SG-based learning and that theories are already applied in several studies, there remains a theoretical application gap in evaluating the levels of cognitive absorption of players. This is critical because KA analyses conducted at a surface level are insufficient to reveal the degree to which games genuinely facilitate cognitive learning.

2.2.1 Game Design Elements that Facilitate Learning: The Identified Methodological Gap

Modern theories describe effective learning as experiential, active, problem-based, and provides immediate feedback (Boyle, Connolly & Hainery, 2011). Crucially, the structured guidance on properly developing a SG remains limited (Boyle, Connolly & Hainery, 2011). Designing a well-functioning SG may proceed along the research trajectories focused either on outcome evaluation of the dynamics of player-computer interactions (Marsh, 2010). These approaches present distinct yet complementary lenses on game design. However, systematic reviews have repeatedly underscored the need to investigate which specific game features most effectively support learning (Boyle et al., 2016). Nine years after the recommendation of Boyle and colleagues (2016), concrete empirical evidence remains elusive, with a few exceptions that attempted to qualitatively describe some game features. Against this backdrop, the current research seeks to address the urgency to perform more in-depth methodology-based investigation, providing evidence of game elements and their pedagogical efficacy.

SGs are conglomerated with elements such as game mechanics, frames, graphics, and artistic narratives (Gros, 2007). Several existing research described game elements, interactions, and their impacts in learning. One systematic review performed by Ravyse et al. (2017) was found to encompass almost all these common attributes, specifically highlighting the success factors for SGs to enhance learning. Ravyse and colleagues (2017) revealed five central themes crucial in making games intertwined with pedagogical content, namely backstory and production, realism, artificial intelligence and adaptivity, interaction, and feedback and debriefing.

While the categorisation of Ravyse et al. (2017) is exhaustive for encompassing the findings of several studies, there are confounding and competing conclusions that need clarity (Annex D). For instance, while Bengston et al. (2021) advocate for open-ended content creation by players to foster collaboration, Waeber et al. (2023) caution that such freedom can make it difficult to measure the educational impact of games. Similarly, Bellotti et al. (2012) and Ke (2008) advanced the value of immersive, and context-linked narratives, yet Waeber et al. (2023) found that overly mysterious or complex storylines can actually distract players from absorbing key scientific concepts. This tension highlights a critical balance between engagement and clarity. Moreover, Cosmo and Tuchen (2020) emphasise role-playing and flexible decision-making as beneficial, as such was complimented by Bolijn et al.'s (2022) report that poorly functioning mechanics can hinder learning by failing to convincingly absorb ecological processes. Further discrepancies emerge in discussions around realism and competition. While Bolijn et al. (2022) and Byun & Loh (2015) suggest that 3D environments and realism increase engagement by simulating physical experiences, Ravyse et al. (2017) stress the importance of abstraction and expert-informed design, particularly in the impossibility of fully replicating the real world in digital formats. In terms of game competitiveness, reward systems and leaderboards are widely endorsed by Miao et al. (2022) and Cheng & Annetta (2012) as motivators, however, Ravyse et al. (2017) and Menconi et al. (2025) emphasised that competition, especially under time constraints, can induce anxiety and detract from educational objectives.

Despite the mismatch found on several studies of what elements truly foster and hinder learning, the systematic review of Ravyse et al. (2017) deserves highlighting. The detailed comparison of the earlier literature (Annex A) is summarised below:

a. **Backstory and Production:** Stories that enable players to perform operations to grasp complex environmental issues are found to be relevant in increasing engagements. For instance, a review done by Maharaj (2015) enumerated three SGs demonstrating how game activities such as taking down enemies with axes to protect trees, and purchasing plants and planting tree as a tree diversity simulator. Similarly, inviting players to explore the financial dimension in reinforcing programs is also found helpful in understanding forestry and agriculture (Batson & Coleman, 2008). Dernat et al., (2025) cited Plass et al., (2015) on their contributions about how altering perspectives can create environments that are immersive, aiding in the facilitation of acquiring knowledge and their application. Sensory and stimuli, on the one hand, increases the players' engagement with the learning material, emphasising the need for appealing storyline (Ke & Abras, 2013; Ke, 2008). The influence of storylines is stressed by Bellotti et al. (2012), emphasising that beyond simply creating attractive presentations, stories should be linked with content and that context should match the narrative (Chent et al., 2014; Couceoro et al., 2013). This is echoed by Waeber et al. (2023) reporting that storyline such as detective narration and problem-solving gameplay was found to be distracting to some players to fully grasp the entire scientific content. Their results added that having too much mystery in the game can dilute the attention to detailed biological processes intended for learning (Waeber et al., 2023). Similarly, overly rich presentation of information can distract the students from the learning tasks (Ke & Abras, 2013). On the one hand, Bengston et al. (2021) recommended to enable players write their own content in card-related games (e.g. IMPACT: Forestry edition), increasing collaboration during the game. Contrary to this suggestion, creating open ended solution spaces where players can navigate multiple strategies can pose challenges in assessing the true impact of educational effectiveness (Waeber et al., 2023).

b. **Realism:** The 3D environment nature of the game can immerse players, for instance, making them feel like they are actually managing a reforestation project (Bolijn et al., 2022). 3D models combined with realistic sound enables users experience the physical space (Baranowski et al., 2011; Byun & Loh, 2015). The simulations embedded also provide opportunity for problem-solving skills to develop while improving the illustrative nature of the game, thereby increasing the interactions among players to find solutions (Waeber et al., 2023). Ravyse, et al. (2017) acknowledged the fact that not everything in real-life world can be replicated in the digital world. Hence, abstraction is acceptable in game design so long as it is accompanied with expert understanding of the content and pedagogical experts ensure the proper integration of real-life representatives into the game (Hong et al., 2013). Although realism and abstraction can be tailored to specific audience, 2D games are viewed as unsophisticated while games designed for high schools are more realistically looking and more complex (Dickey, 2011). Achieving such balance between formal and informality is also just as crucial. For example, informality can lose some of the valuable educational gains (Ebrahim et al., 201). Themed games such as exogenous fantasy environments are found to be less effective in facilitating learning when compared to storyline embedded in the learning material (Ke, 2008).

c. **Artificial Intelligence and adaptivity**: Integration of artificial intelligence in SG is still at increasingly being explored. It can be seen in the form of "a) adjustments within the game through agents and b) adjustments of the game itself by means of adaptivity" (Ravyse et al., 2017, p. 50). Oftentimes agents can act in the form of non-player characters (NPCs) who flag players when triggers are activated in the game. NPCs provide an alternative for students who are more accustomed to learning from facial expressions and intonation of their teachers (Johnson & Mayer, 2010) providing a new form of learning and information resource (Van Eck, 2006). Adaptivity, on the one hand, includes the change in game's difficulty based on the players' profiles indicating significant learning especially in controlled groups (Soflano et al., 2015). Adaptivity can be closely linked with scaffolding as an approach to learning. Scaffolding promotes a gradual introduction of levels difficulty and practice levels so players can acclimatise to the game's interfaces (Ha¨ma¨la¨inen 2011; Hwang et al., 2013; Ke and Abras, 2013; Van Eck, 2006).

d. **Interaction**: Player-to-player interactions are identified as leading game success factor (Ravyse et al., 2017). Whenever players share tactics and solutions with one another, collaboration, even if not intended for the game, becomes possible. On the one hand, accessibility and navigating through games can be both challenging and helpful for players. A game developed in Tabletopia, a widely used software to develop games, was found to be difficult to use and consumes a large amount of internet connections (Helmberger, et al., 2022). This is contrary to the report of Boljin et al. (2022) indicating that web-based games increase accessibility to participants. Digital format games are viewed as an enriching learning activity to reach a broader public response (Cosme & Turchen, 2020). Physical haptic tabletop games are also found to increase the exchanges among players and incite emotional engagements. Screen sizes should also be considered with at least 58 mm (2.28 in) size to foster better learning (Maniar et al., 2007). The general rule of thumb is for game developers to avoid complex interfaces because it would require a lot from novice players to become accustomed to the game and may induce cognitive load. Game interfaces should have straightforward dynamics (Gonza´lez-Gonza´lez & Blanco-Izquierdo (2012). Games with hard-to-control mechanics such as the back-and-forth use of mouse and keyboards contributes to students' loss of interest (Zin & Yue, 2013). Competition can also raise anxiety among players making them quit the game or avoid the learning aspects (Ravyse et al., 2017).

e. **Feedback and Debriefing**: Several studies described reward systems as the most used learning tool in gamification (Miao et al., 2022). Rewards are utilised specifically to enhance user engagement and fosters behaviour (Radziszweski et al., 2021) and followed by equally helpful tools like feedback, competition, points, and goals among others (Miao et al., 2022). Game rewards should also be linked to learning outcomes to increase the likelihood of absorbing the intended impact of the game (Kiili, 2005). Apart from reward systems, quick in-game feedback and instant updates are two game designs that can provide immediate cause and effect scheme of the players' actions and showcase competitive standing, respectively (Cheng and Annetta (2012); Johnson & Mayer (2010); Cheng et al. (2015); Kiili (2005); Kuk et al. (2012). Challenges and meanings, despite the two being categorically under the interaction domain, can also enhance the learning of players (Miao et al., 2022). Meaning provides specific actions that can create persuasive systems for players (Huber & Hilty, 2015). For instance, "persuade" as a meaning meant to change the behaviour towards environmental protection. Feedback mechanisms also improve memory and retention (Goodison, 2001). Time is also another worthy opponent of game players that can channel collaborative learning (Admiraal et al. 2014; Ha¨ma¨la¨inen, 2011; Kiili 2005; Schmitz et al. 2015). However, players competing against time may encourage them to prioritise the speed instead of the educational content (Menconi et al., 2025). Since SGs are highly embedded with constructivist theory, implementing time limits is counter-intuitive to explore learning. Due to the competition against clock, players may find it difficult to satisfy both learning and playing. Moreover, inciting competition against other players is often discouraged especially if the learning aspect remains the focus of the research. Lastly, debriefing is considered to be the most important moment of the game for players to process and consolidate their in-game experiences (Crookall, 2014). The tool can be in the form of generated progress-tacking reports and memorable recollection of the game. Gonza´lez-Gonza´lez et al. (2014) mentioned that chat logs can serve as progress tacking suitable for post-game debriefing. This was supported by the review of Ravyse et al. (2017) claiming that chat interfaces enhance the success of multi-player SGs even if conversations are not about the learning material.

The current study still acknowledges the immense work done by Ravyse et al. (2017) but arguably, more effort has to be undertaken. Specifically, exploring the game elements that actually capture the learning effectiveness among players. Hence, instead of assessing the SGs as a whole in imparting knowledge transfer, the current research deepens the scholarship by breaking down the elements within the game that help facilitate cognitive thinking processes. Furthering the exploration into game elements briefly shapes the methodological gap of the study.

2.2.2 The Game Elements that inspire the Methodological Gap of the Study

Arguably, the over-exploration of interaction-centred studies (e.g. player to player interaction, player to game rules interactions) overlook the foundational game elements that activate what players learn with and how they engage with content. Game elements conceptualisations vary. The examples can stem from scaffolding or the gradual introduction of concepts to acclimatise players, narrative, visual and auditory aesthetics, virtual environments, avatars and even rewards systems. A common recommendation that is frequently advanced is the need to break down these elements that capture and retain player attention (Menconi et al., 2025) and digest which elements actually contribute to learning (Boyle et al., 2016), particularly in KA. Drawing from this proposal, empirically investigating the distinct contribution of each game element is just as crucial as assessing the game experience and efficacy as a whole. Several studies already exist attempting to laser focus on game elements such as a) trivia (Aryaei, 2025; Vega-Gorgojo, 2019; Rai & Beck; 2017; Elm et al., 2016), b) quizzes (Karavidas, et al., 2024; Reimer et al., 2015; Brandão & Carvalho, 2014), c) in-game management related mechanics (Puritat, 2019; Seibert & Vis, 2012; Depigny & Michelin, 2007) and d) game events (Wouters et al., 2017; Van der Spek, 2013). For the sake of transparency, it is worth-mentioning that the attempt is not groundbreaking, yet the infancy of the siloed game element studies in SG research still demands further empirical investigation.

a. **Trivia.** Aryaei (2025) explores an AI-powered trivia game inspired by Duolingo, Who Wants to be a Millionaire? and AI Dungeon. The study addresses the repetitiveness and limited adaptability of trivia games, despite being popular (Argaei, 2025). Results demonstrate that AI-driven game design can contribute to the broader discussion in educational engagement. On the one hand, Clover Quiz, a turn-based multiplayer trivia game uses structured data from Wikipedia (Vega-Gorgojo, 2019). The research demonstrates the potentials of semantic technologies for collecting data and automated generation of multiple-choice questions. Another notable example is the game CLEVER, an integrate trivia-strategy game designed to encourage knowledge management skills at work (Elm et al., 2016) and Rai & Beck (2017) who used a trivia-style SG to assess the behavioural antecedents toward solar energy among residential households using a trivia-style SG.

b. **Quiz.** Karavidas et al. (2024) implore an online quiz that act similarly as a SG to assess the knowledge of web technologies among students. Meanwhile, quiz, simulation, and adventure-type of learning were compared wherein results stress that gender can play roles in evaluating students' attitudes and perceptions when engaging with SG. Lastly, Brandão & Carvalho (2014) create "GAME QUIZ", an online platform which intends to enhance the interest of children in promoting Information and Communication Technology in Portugal.

c. **In-game management**. Madani et al. (2017) compiled SG on environmental management. Meta-analysis result emphasises that conflict resolution, water management, irrigation, and ecosystem ecology were some of the ubiquitous themes in environmental management. Notable in-game management-related (direct use of resources to address game challenges) SGs include Aqua Republica which challenges players to manage a catchment similar to real-life scenarios (Puritat, 2019; Madani et al., 2017), and Irrigania where players have to manage shared surface and ground water resources within the village (Seibert & Vis, 2012). Moreover, Shrub Battle trains future rural planners become aware of the complex interrelationships between agricultural practices in farming (Depigny & Michelin, 2007) while a game targets to promote awareness in finding the middle ground decision between forestry practitioners and herdsmen were explored in Industrail Chlorine Transport Metagame Sylvopast (Bots & Hermans, 2003).

d. **Game events**. Lastly, the game Code Red Triage designed by der Spek et al. (2012) explores three surprising events that trigger decision-making activities. The findings reveal that participants obtained increased knowledge, entailing that surprising events can foster deeper learning. Meanwhile, a study on surprising events shows activated triggers, for instance, non-player characters, indicating that surprises can be beneficial for higher level students. The study stresses that narrative techniques as surprises can be integrated in game-based learning (Wouters et al., 2016). On the similar vein of surprising events, details the role of surprising events for unwinnable games. The research mentioned that in-game surprises evoke players to assess their game status (i.e. winning or losing) (Isnanda et al., 2023). Key takeaway from the work suggests that delaying the revelation of surprising events promote the same level of donation as part of social change (Isnanda et al., 2023).

Trivia and quizzes are two of the popular mechanisms to deliver messages on environmental issues mostly catering the educational capacities of children (Razali et al., 2022). Quiz is also considered as the simplest type of SG that are widely known for quick acquired knowledge assessment (Reimer & Schrader, 2015). Contextualisation of complex systems (e.g. carbon cycle, Razali et al., 2022) an underexplored topic, which in a way, aligns with the lack of system-centred SG. This is where the addition of in-game management comes handy wherein beyond fact-sharing, environmental processes can be further explored. Games designed to sharpen management skills, particularly in environmental sustainability challenges, are effective in imparting first-hand experience that is otherwise costly, or difficult to implement in reality (Madani, Pierce, Mirchi, 2017). Meanwhile, the addition of game events that trigger decision-making create uncertainty, which potentially heighten the players cognitive interest (Campion, Martins & Wilhelm, 2009). Game events can also trigger players to trust their earlier preconceptions of the game which entails them reevaluating what they know, what they have acquired and have missed from the game (Kitnsch, 1980). This situation heightens cognitive attention, potentially stimulating better knowledge absorption (Wouters, et al., 2016).

Conversely, there still remains gaps that requiring bridging and unpacking, making the four game elements worth-exploring. To the best of author's knowledge, combining game elements such as trivia, quizzes, in-game management of resources, and game events, albeit concurrently integrated in one SG, have never been altogether evaluated empirically.

2.2.3 Sustainability Compass

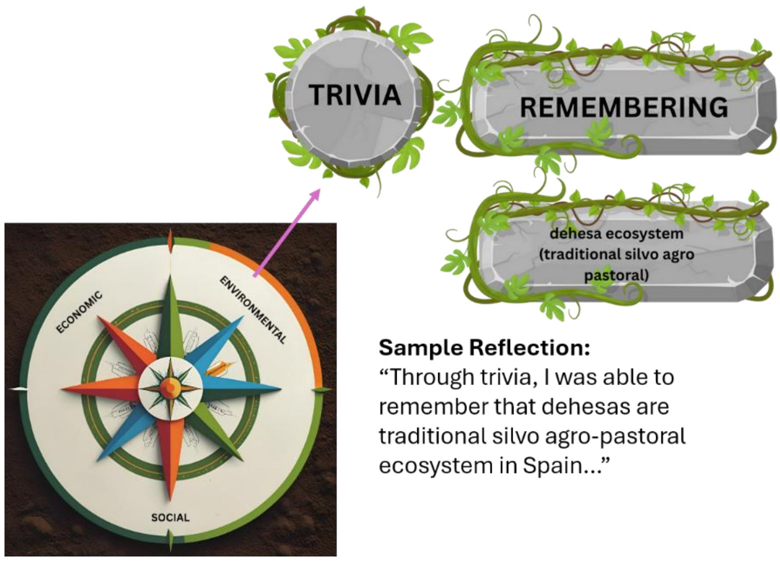


Figure 5. The initial conceptualisation of the Cognitive sustainability compass shown to players to provide example of how to construct one.

Apart from combining the aforementioned game elements, the study also introduces an innovative intervention to address the methodological gap: the Cognitive Sustainability Compass (Figure 5). For context, the Sustainability Compass is an emerging tool or framework that fosters social learning to address sustainability (Sajeva et al., 2024). The intelligent use of compass to expand the three pillars of sustainability has been applied into several contexts. For instance, the Agri Sustainability Compass, developed by the European Union, details 20 key sustainability indicators (Food and Agriculture Organisation, n.d.; European Commission, n.d). Likewise, Sajeva et al. (2024) used the Sustainability Compass through case studies in Finland and Estonia contextualised in cross-border aquaculture and Finnish wind energy project. Another interpretation integrates several frameworks to create a cohesive set of metrics for food systems (Hebinck et al., 2021). Lastly, using an evaluation tool from absolute 0-100 performance scale, The Compass Index of Sustainability reflects its adaptability from small communities to larger regions to address sustainable development (AtKisson & Hatcher, 2005).

Integrating the Sustainability Compass in the current study's exploration presents two opportunities. Firstly, the flexibility of the tool provides enough room for innovation and contextualisation within the intended learning output of the study (i.e teaching Pc). The approach enables assessment of KA outside the limits of the game (e.g. gameplay, virtual environment, game rules). Such method widens the possibility of evaluating players' ability to expand the knowledge their acquired to wider issues beyond the learning objectives, such as the potential contextualisation of players within the three pillars of sustainability. Secondly, the compass may complement the proposal that more investigation is much needed to assess creativity in game-based learning (Shute & Rahimi, 2021), albeit, argumentatively, will be outside of the limits of the game. Since the current research is firmly situated within the domain of cognitive processes, it is both reasonable and necessary to incorporate the full six hierarchies of BCD, be it the facilitation occurring inside (e.g. during gameplay) or outside the game (post-game reflection). Debriefing is considered to be an important component of gameplay where players can consolidate and reflect on their experience (Crookall, 2014), which the Sustainability Compass can provide space for.

To the author's best knowledge, the complementary assessment both during game play and post-game reflection has yet to be done, particularly the use of partial least equation modelling and sustainability compass as complementary debriefing tools. The Cognitive Sustainability Compass is the first of its kind to use the sustainability compass concept as a post-game reflective tool while simultaneously completing the full six-level hierarchy facilitation of BCD. What makes the approach truly unique is its dual role. The cognitive compass both captures immediate evidence of cognitive skill development but also bridges the gameplay outcomes to longer-term sustainability thinking. By embedding social, environmental and economic lenses within the debriefing process, the compass extends conventional knowledge tests and replaces with holistic framework for translating in-game learning into real world sustainability insights.

2.3 Serious Games in Pest Management: The Empirical Gap

The application of SG in forestry has only emerged after 2015 (Hernandez-Aguilera et al., 2020). Nearly a decade after, the literature review of the current study still suffered from the lack of sufficient material (n=10) in the domains of forestry, and tree health, particularly in pest management. This presents a significant window to explore empirical investigations in SG research by fortifying the roles of SG in agriculture, testing pedagogical innovations in forestry and advancing sustainability issues. The conservation and climate risk sectors being predicted to shape the themes in SG arena (Hernandez-Aguilera et al., 2020) lay the groundwork for pest management as more empirical research is required to fully utilise the power and impact of digital SG in facilitating KA.

2.3.1 Forestry, Tree Health and Pest Management as Unchartered Territories in digital SG research

A total of 10 SG-focused studies, where 9 are empirical evidences, were compiled in the current research (Annex A). The topics covered a larger umbrella in forestry, tree health, and pest management. Specifically, majority of the games compared aimed to increase public awareness in cross-cutting issues such as reforestation, urban tree diversity, forest futures, illegal logging, and IPM. Socio-ecological forestry issues like deforestation and illegal logging were explored in MineSet and Forest Ranger, respectively. MineSet is a digital role-playing game developed to facilitate engaging experiences in managing deforestation issues (Waeber et al., 2023) while Forest Ranger uses digital 2D interfaces to inform the public about illegal logging. Similarly, in an unfinished game called Save A Tree, characters attempting to cut down trees were taken down by players using axes, albeit, requiring less violent features for future improvement (Maharaj, 2015). Maharaj (2015) also reported two similar uncompleted game as a result of the competition "Gamification for Tree Health". Protect the Planet has a catchy musical theme embedded in the game with features effective for children about teaching plant health. Tree Diversity Simulator, on the one hand, enables players to purchase and plant trees. Ecological components such as disease, economic transactions between players and other characters are some of the planned features to be added in the future (Maharaj, 2015).

Apart from games tackling complex socio-ecological challenges, solution- building-centred games were also included in the literature review. Benni's Forest teaches players about reforestation practices and its coupled complexities in an immersive 3D simulation game (Bolijn et al., 2022) while ES-Hunt uses available tree cadastres (detailed registry of trees) to learn concepts such as tree diversity and ecosystem services (Menconi et al., 2025). Notably, the game IMPACT: Forestry Edition trains professionals and relevant actors to creatively and holistically envision forest futures (Bengston et al., 2021). In the similar vein, Calendon uses financial game mechanics, reinforcing the students with the strategies in forestry programs (Batson & Coleman, 2008). The game features have potentials to learn about pests and diseases appreciating the roles of tree diversity in resilience-building (Coleman, 2017). Games such as Calendon (Batson & Coleman, 2008) and the result of Gamification for Tree Health competition (Maharaj, 2015) showed the already existing interests in tree health pedagogy using SG; a case that may also apply in IPM.

Three games broadly used for students are worth-mentioning, potentially paving ways for other topics under tree health such as pest management to emerge (Figure 6). Insect World is an analogue card game with role-playing game interactions teaches insect taxonomy, physiology, morphology and behaviour embedded in the 288 cards (Cosme & Turchen, 2020). A key finding from the research highlighted that players were able to create strategies based on the information from each card and manual facilitated the linkage between the insect and another card (Cosme & Turchen, 2020). Additionally, Spotted-Stop-It is another 2D mobile game that aims to incite the interests and participation as well as disseminate knowledge of the management of pests (de la Vega et al., 2022). The game was specifically inspired by the soft-skin fruit pest spotted wing Drosophila (Dropohila suzukii). Through image information provided in the game without the overreliance on pre-knowledge about insects. The narrative and association, participants were able to identify the spotted wing Dropohila. The management practices integrated in

the game enabled participants to identify practices such as the harvest frequency, sanitation and alternative hosts during the gameplay (de la Vega et al., 2022). Lastly, Pest Quest, with its two game versions that come

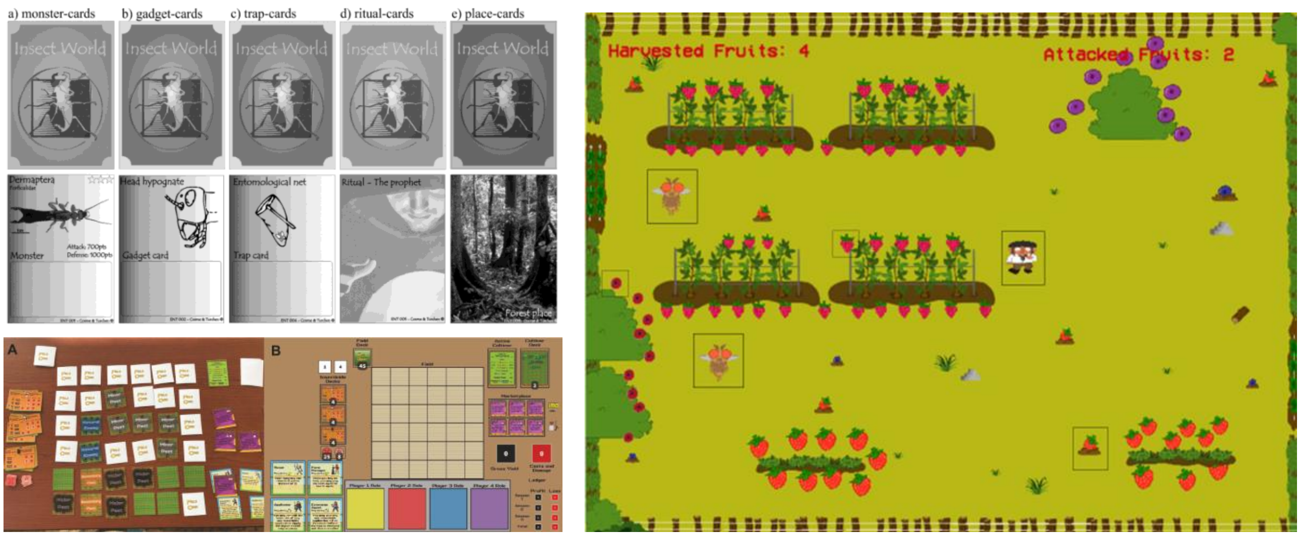


Figure 6. (Top Left) Sample of cards in the InsectWorld game; (Right) A screenshot of the mobile game Spotted-Stop-It; (Bottom left) Images of the tabletop and digital version of Pest Quest. Sources: (Top Left) Cosme & Turchen, 2020; (Right) de la Vega et al., 2022; (Bottom left) Helmberger et al., 2022.

in digital and analogue formats, aims to increase the knowledge of the players in three domains, namely IPM terminologies, philosophies and decision-making (Helmberger et al., 2022). The students who underwent the treatment said their understanding about insect pest management, the advantages and disadvantages of pesticides and the economics of farming have improved significantly (Helmberger et al., 2022).

2.3.2 The Empirical Gap of the Study

All the compiled studies stress the importance of connecting game design with the learning intent. Helmberger and colleagues (2022) cited that their assessment methods would have been better if the kinds of learning the game provides are included. Meanwhile, de la Vega et al., (2022) suggested that the game can be adopted globally with a few changes in the farmer and non-crop alternative hosts alongside different language versions as future game features. Lastly, Cosme & Turchen (2020) highlighted that the amount of information required to build a strategy and read the manual posed difficulties among players. The current study posits that such limitations can be addressed in an empirical context. Taken into consideration the methodological and theoretical application gap discussed earlier, this study embraces the recommendations to assess learning in the lens of KA (Helmberger et al., 2022) while developing ways to avoid the overly rich presentation of information (Cosme & Turchen, 2020), and other related literature (Annex A-C). Similarly, de la Vega et al.'s (2022) call for non-crop alternative hosts make the invasive pathogen *Pc* as a compelling empirical case. Phytopthora's devastating effects in holm and cork oaks in the Dehesa ecosystem in Spain shows promising contextualisation, aiding the current need for more advanced SG-research in pest management.

To successfully integrate Pc as the empirical case study, the four game elements are defined below, drawing inspirations from earlier studies.

a) **Trivia.** Trivia refers to short, fact-based questions or statements designed to provide players with essential background knowledge about *Pc*, including its characteristics, history, and ecological impact. The trivia drew inspiration from Cosme & Turchen (2020)'s findings where narrative and information from game cards and manuals can facilitate the linkage between technical concepts, thereby, encouraging the players to create strategies based on the information provided.

b) **Quiz.** Quiz consists of structured questions that test the player's understanding of the content presented in each level of the game. These include multiple-choice, and matching questions related to the pathogen's spread mechanisms, management practices, and general knowledge. Quizzes help assess how much players have learned and retained. The inclusion of economic-centred quizzes adapted the findings of Batson & Coleman (2008) where financial components of the game CALENDON invites players to tackle strategies that can result in successful forestry programs. Additionally, the inclusion of characters in the game and game rules allowing collaboration when answering quizzes and treating infected trees replicate Waeber and colleagues (2023)'s finding on bringing stakeholder roles enables students to learn about stakeholder engagements in addressing deforestation.

c) **In-game management or In-game resource management.** In-game management refers to the decision-making tasks players perform to simulate controlling the spread of *Pc*. This includes selecting and applying sustainable biological practices such as the Trichoderma spp. application, use of calcium fertilizer, erecting a fence around trees and adding a root barrier. In-game management draws inspiration from Spotted-Stop-It game (de la Vega et al., 2022) where management practices enabled participants to identify solutions such as harvest frequency, sanitation, and alternative hosts during game play. Moreover, empirically investigating this game element was also based on the results of Waeber et al. (2023) where simulations can provide problem-solving skill development among players especially when games have illustrative examples that increase the interactions and encourage solution-building. Similarly, role-playing games (RPG) and RPG-related designs offer flexibility in decision making and problem-solving engagements (Cosme & Turchen, 2020) which the in-game resource management attempts to mimic.

d) **Game events.** Events are interactive scenarios or problem-solving activities embedded in the game that require players to apply higher-order thinking skills—such as analysing, applying and evaluating. These include the analysis of the infestation through the treasure box which activates transmission, and the pop-up events that challenge players to apply the knowledge they *just* unlocked. Game events build on recommendation of Ruta (2009) where players who are given opportunity to apply the knowledge to different contexts complements learning beyond just providing information. Additionally, game events have appealing storyline such as sudden pour of rain, farm activities like chopping down of trees that facilitate pathogen transmission, and quick challenge activation after unlocking trivia. Storylines like these align with recommendations to include learning material with narratives and allows players to progress once they display correct behaviour within the game (Ravyse et al., 2017; Ke & Abras, 2013; Ke, 2008).

e) **All Game Design.** It is worth-mentioning that there are research findings that were encapsulated on all four game elements. These include creating a storyline and context that is connected to content rather than the intent of creating attractive visuals (Chent et al., 2014; Coucero et al., 2013; Bellotti et al., 2012). Reward system which is also embedded on all four game elements also enhances user engagement and fosters behaviour (Radziszweski et al., 2021; Helmefalk & Rosenlund, 2020; Cwil & Barnik, 2018). The game also follows the recommendation of Kiili (2005) to link the game rewards to the learning outcome.

3. STATEMENT OF THE PROBLEM, GOALS, OBJECTIVES AND HYPOTHESES

The fundamental issues identified from the literature review reinforce the theoretical application, methodological, and empirical gaps of the current study, requiring more efforts to fully understand SG's effectiveness in KA and its application in sustainability issues. Cognitive understanding (or KA), despite being one of the most commonly evaluated outcomes, is mainly analysed through a broad lens. Existing game effectiveness literature assesses knowledge absorption at a surface level without breaking down the cognitive process participants have gained. While relevant theories exist (e.g. cognitive, behaviourism, constructivism), there is a lack of operationalisation on how frameworks can be used to systematically analyse the different hierarchies of learning. BCD (Anderson & Krathwohl, 2001; Bloom et al., 1956) offers a promising approach to address such conceptualisation deficiency due to being widely used in guiding educators in pedagogical content structuring. Nonetheless, there still remains research windows for Bloom's taxonomy to operationalise in digital SG arena, heavily shaping the theoretical application gap of the study. In terms of methodological research gap, several exploratory yet pioneering studies have catapulted game design-focused understanding for the last three decades. The literature review, however, emphasised that foundational game design components remain underexplored, suggesting future research on which game elements actually shape learning. This is critical because the research community have contrasting conclusions on some game aspects. For instance, immersive environment and narratives are found effective in KA. However, caution must be exercised in game development since presenting overly mysterious and complex storylines can overpower the intended learning concepts. This nuanced interplay underscores the need to empirically isolate and assess specific design features rather than evaluate SG's effectiveness in KA *as a whole.*

Finally, the literature review showed that there is a lack of SG applications in pest management despite the broader umbrella topics such as forestry and agroforestry already being explored. Promising games such as *Spotted-Stop-It*, *Pest Quest*, and *Insect World* have demonstrated the power of SG in facilitating knowledge in pest practices. Yet, the field of invasive species remains nascent with many more potential game design inspirations from invasion biology, demanding more empirical evidences and contextualisation. Drawing from the recommendations of the earlier SGs alongside the identified theoretical application and methodological gaps, the case of *Pc* is proposed to be the main empirical case study. With the pathogen's three-decade long destructive impacts in Spain's Dehesa ecosystem, the research argues the relevancy of Pc to contribute in pest management education and digital SG research.

3.1 Problems of the study

Given the knowledge gaps identified, this study specifically addresses the general question: Can a serious game based on *Pc* (a) facilitate the learner's KA about the pathogen across different cognitive thinking process based on BCD, and (b) contextualise the knowledge the participants acquired to the three pillars of sustainability? Specifically, two sub-questions govern the evidential exploration of the study, namely (a) Which specific game design elements have the strongest influence to the learners' KA, particularly the players' cognitive process and learning content? and (b) What dominant cognitive linkages among the three sustainability pillars, game elements, and cognitive processes can emerge after playing the game?

3.2 Objectives of the Study

The overarching goal of the study is to create a digital SG incorporating *Pc* as the empirical case study that can be accessed online and empirically tested to evaluate its efficacy. The objectives are divided into three domains aligning with the research questions and overall goal of the study. The sections involve game development, game testing, and performing quantitative and qualitative analysis.

1. Game Development:

a. To systematically develop game mechanics that reflect the real-world infestation mechanisms and management practices in handling *Pc*. The mechanics include the rules of the game and scoring matrix based on the review of related literature and the results of the key informant interviews.

b. To create an internet-based accessible and navigable digital SG contextualising *Pc* as the empirical case.

c. To test the produced digital SG with university-level students. The target groups are students exclusively pursuing Master's degree and PhD education.

2.**Game Testing:**

a. To facilitate the game play from teaching the basic rules and mechanics of the game to documenting the issues that may arise, and recording the in-game performance of players.

b. To assist the participants when answering the survey and facilitate the card-sorting activity (i.e. Cognitive Sustainability Compass) post gameplay.

c. To gather the perspectives of the players during gameplay, specifically analysing the design elements that facilitated knowledge absorption and facilitation about *Pc*.

3.**Quantitative and Qualitative Analysis:**

a. To perform a sound quantitative and qualitative analysis of the data from the survey and key informant interviews.

b. To analyse the in-game performance recordings, and to critically assess the specific game design elements that contributed in the learning facilitation during game play.

c. To investigate which among the assessed game elements are helpful in aiding knowledge absorption to the players, later assisting in conceptual reflections on the three pillars of sustainability.

Overall, this research aims (a) to provide empirical evidences on the efficacy of specific game design elements that facilitated content understanding (or KA) about *Pc*, and (b) evidential support about the application of knowledge acquired after playing the digital game, specifically to the three pillars of sustainability. The development of the board game serves as the main research intervention serving as the central output of the study supported by empirical data.

3.3 Hypotheses of the Study

The study posits that the *Pc*-inspired SG will serve as an effective tool to improve the knowledge of the participants about the spread mechanisms and infestation management. The results will demonstrate the knowledge understanding across multiple cognitive levels, albeit, anticipation on stronger facilitation over the other is expected. Specifically, the study hypothesises that trivia and quiz will facilitate lower-order thinking processes, remembering and understanding, while in-game management and game events will support middle- to higher-order thinking skills. Trivia likely supporting remembering stems from the study that typographical cues which are inherent among trivia can improve facts recall (Roberts, 2016). Meanwhile, quiz is more likely be coupled to understanding and analysing because the element can act as a tool for quick understanding or comprehension assessment (Shute, 2011). There is also a chance that quiz can manifest as a facilitator of remembering since literature claims that embedded checks can aid in memory retention (Roediger et al., 2006) and recall accuracy (Taveira-Gomes et al., 2015). Moreover, quiz not penetrating the higher-order skills can be bolstered by the study of Stranger-Hall (2012) stating that multiple-choice exams hinder higher thinking in science-related classes. In general, digital game-based learning promotes higher-order skills (Kgosietsile, 2023) while there is no pertinent evidence that game events and even tasks that require resource management would facilitate higher cognitive responses. Despite yet, given that interactive gameplay, scaffolded progression or the gradual introduction of game mechanics, and curriculum alignment concretises higher thinking process in SGs (Awang et al., 2024), the study hypothesises that in-game management and game events can also validate the successful facilitation of advanced thinking skills.

Moreover, the research posits that players would cite more environmental sustainability concepts than social and economic sustainability reflections. Despite no study exists asserting that environmental pillars are expected to emerge more evidently when compared to social or economic dimensions, the wedding cake model illustrates that society lies within the biosphere while economy is embedded within society (Folke, et al., 2016). The framework argues that environment acts as the foundational system through which society and economy depends on (Folke, et al., 2016), thereby, underscoring the hypothesis that environmental sustainability themes would dominate the sustainability compass. To extend the hypothesis, studies show that social issues around sustainability are "inherently difficult to break down logically" (Isgren & Longo, 2024, p. 821). Additionally, the mere fact that social sustainability serves as a vague phrase to encompass wide ranging outcomes create conceptual overload, confusing definitions and confounding languages (Isgren & Longo, 2024). Lastly, the study expects that the sustainability compass would be least populated with economy-related responses. Given the inherently system complexity of economic concepts, capturing their essence would require building comprehensive mental modelling, and trade-off mechanisms (Spangenberg, 2005), which exceeds the analytical capabilities of non-economic proficient players.

4. METHODOLOGY

The study utilises a mixed-method approach. The remaining parts of this section detail the research design, the relevant theoretical and conceptual frameworks, the sampling instruments and materials, the data-gathering procedure, and the analyses performed.

4.1 Research Design

The research design begins from the overarching aim of this study, namely to generate empirical evidences on the efficacy of game elements in cognitive process facilitation (Figure 7). A total of 15 related literature was consulted, analysed and organised (Annex A-D) to identify a) the current status of SG research in agriculture, sustainability, forestry, tree health, and pest management. As previously discussed, three knowledge gaps were addressed, circumnavigating the theoretical application, methodological, and empirical gaps. Proposed solutions are parallel to the gaps identified. The solution involves a) undertaking a deeper evaluation on the assessment of five cognitive thinking processes derived from BCD, b) departure from the widely explored game interaction-focused studies, instead underlining the importance of the evaluation of game elements that facilitate five cognitive thinking processes, and facilitate a cord-sorting activity to create Cognitive Sustainability Compass as a post-game reflection outside the game, and lastly c) contextualise *Pc* as an empirical case study.

ADDIE model, a widely accepted model in creating instructional materials was adopted as the guiding principle in game development and testing (Figure 8). Furthermore, the mixed-method approach comprised three individualised and integrated clustered analysis. Firstly, the quantitative analysis utilises Partial Least Squares Structural Equation Modelling, addressing the first and second proposed solution to tackle methodological and theoretical application gaps. Secondly, the qualitative analysis harnesses the participant responses post-gameplay. The data covers the positive and negative feedback regarding the players interaction with the game elements as well as suggestions in improving the game. Lastly, the Cognitive Sustainability Compass was used to assess whether gamers can quickly use their acquired knowledge in wider sustainability challenges. The research design ends with writing the key takeaways, acknowledging the limitations, and advancing the route of future studies in the SG discipline.

4.2 Prescriptive Research

The study employs a prescriptive research design. Prescriptive research constitutes applied research inquiry wherein the development of solutions or new ideas are central to the study (Wollman, 2012). The implications generally tackled under this type of approach revolves around the question, "what should be done now?". The current study aligns with this paradigm, given that SGs as tool in acquiring different KA hierarchies is thoroughly and consistently investigated. Moreover, this research paradigm is often used for educational intervention studies (Marley & Levin, 2011), a convergence that resonates with the position of SGs as an effective pedagogical solution.

It is worth-noting the overlap with other research paradigms. The current research also reflects the nature of cross-sectional studies given that the quantitative and qualitative data are collected at one point in time. Explanatory or theory-driven research paradigm also matches the nature of the study provided that specific game elements that influence learning are also broadly analysed, more specifically on the operationalisation of BCD. Additionally, the study does not aim to infer causality between the game elements and the cognitive acquisition of players, rather, the research targets to deduce statistical associations between these variables in the post-game context.

4.3 Population Sampling Technique

A total of 35 participants engaged in game testing and survey completion, while 17 participated in the Cognitive Sustainability Compass making. The study used convenience and self-selection sampling technique to identify the sampling unit. Convenience method is a technique categorized under non-probability sampling wherein the selection of sampling unit is based on convenience of the researcher. Participants that were recruited belong to the academic network of the researcher such as those who are taking the same degree programme (n= 10) (i.e. International Masters of Science in Rural Development), participants that finished the similar degree (n= 2, i.e. IMRD), and academic colleagues (n=10). Participants recruited under convenience sampling probably knew each other, but they had no prior experience with digital board games.

In addition, the participant recruitment also underwent self-selection sampling; another domain under non-probability sampling. This sampling method involves participants (n=13) choosing to take part in the research on their own based on the Participant Recruitment Notice (Annex E) posted on LinkedIn and university newsletter in partnership with several universities in Europe. The recruitment resulted to collaborations with three universities, namely University of Freiburg (Germany), SPU Nitra (Slovakia) and Wageningen University and Research (the Netherlands). The participants recruited from this sampling method are students currently undertaking different environment-related degrees in Europe (n=13).

4.4 Data-gathering Instruments

The primary data collection instrument comprised a structured questionnaire (Annex F) and a card-sorting activity termed as Cognitive Sustainability Compass. The questionnaire includes six sections. The first section documents the socio-demographic profile of participants such as their age, gender, and country of origin. The second section assesses the participants' prior knowledge and experience in playing educational games, whether analogue or digital format. The same questionnaire component also requests the participants' knowledge in life science-centred and university-level courses, and prior work or internship experience related to several environment and agriculture-related areas. Meanwhile, the third section evaluates the satisfaction and engagement of the players while the fourth comprehensively evaluates four game elements examining their assistance in acquiring knowledge during gameplay. The fifth section measures how game testers are able to remember, understand, apply, analyse, and evaluate the game situations and challenges. The structured questionnaire did not enquire about 'creating' as this was later assessed post-gameplay. The last section of the questionnaire encourages participants to provide general feedback both positive and negative, as well as things that can be improved in the game. In average, participants answered the questionnaire for 12 minutes.

Meanwhile, the card-sorting activity aims to capture the highest cognitive hierarchy---create. The task involves matching the four game elements, the five cognitive thinking skills, and the list of sustainability concepts categorising them into environmental, economic, and social concepts. The result of this activity shapes the Cognitive Sustainability Compass that are useful in determining the efficacy of each cognitive hierarchy in understanding sustainability concepts. Each sustainability pillars have ten suggested concepts where participants can reflect on and given the option to add more ideas that were not on the provided themes. Participants are given eight minutes to reflect on the game and match the different cards to suit their reflections after gameplay. During the card-sorting session, the researcher asked several questions to help the participants with the task (Annex G). Majority of the questions encourages the respondents to revisit the knowledge or insights they gained, describe the specific concept or process they understood in the game, and associate environmental, social, and economic challenges that they identified beyond the scenarios the game has presented. In average, participants spent ten minutes discussing their Cognitive Sustainability Compass (Figure 8).

4.5 ADDIE Model

The ADDIE model is a five-phase approach widely employed in the development of learning solutions (Molenda, 2003) (Figure 9). Under Phase 1, Analyse, the theme pronounces the creation of a digital board game that will be accessible online with the main goal of teaching players how to identify spread mechanisms and evaluation of the suitable solutions to stop further pathogen infestation. The goal of the pedagogical digital game responds to the lack of interactive material that focuses on *Pc* where the target audience is university-level students, through which the complexity of the game, narratives, and learning content are specifically tailored for. The second phase, Design, details the learning objectives of the game which are parallel to the overall theme. Specifically, players are expected to learn the basic information about the history of infestation, the ecology, and early symptoms of the tree diesease. Additionally, gamers must also identify the transmission processes, both induced by biophysical and human- and invertebrate-mediated factors. As previously mentioned, scaffolding serves as the pedagogical delivery approach wherein game concepts, objectives, and resources are slowly introduced as players progress in the game. Feedback system is manifested in different forms. For instance, player win different stars as they face pathogen, correctly answer quizzes, fulfil the game challenges through events, and treat infected and protect healthy trees. Moving on to the 3rd phase, Genially was used as the main game development software wherein a total of 6 published articles on *Pc* was utilised to build the trivia, conceptualise the infestation solutions and heavily shape the content and game progression in game events. The first version of the game (Annex H) received critics from profesors and expert in *Pc* (n=5) highlighting the overwhelming graphics due to farm size and visual load. The validators recommended to divide the game to digestible levels where the landscape typology evolves as the game progresses. Meanwhile, similar points for improvement where mentioned by students (n=3), stressing the clear game instructions on how to begin and navigate the game, absence of reward system to motivate players, and excessive visual load that causes confusion. After the consultation, the game was revised and entered the implementation stage. Data-gathering was conducted from June to July, 2025, facilitating 35 players in total. Lastly, three analyses were used to evaluate both in-game performance, and post-game reflections through questionnaires and card-sorting activity.

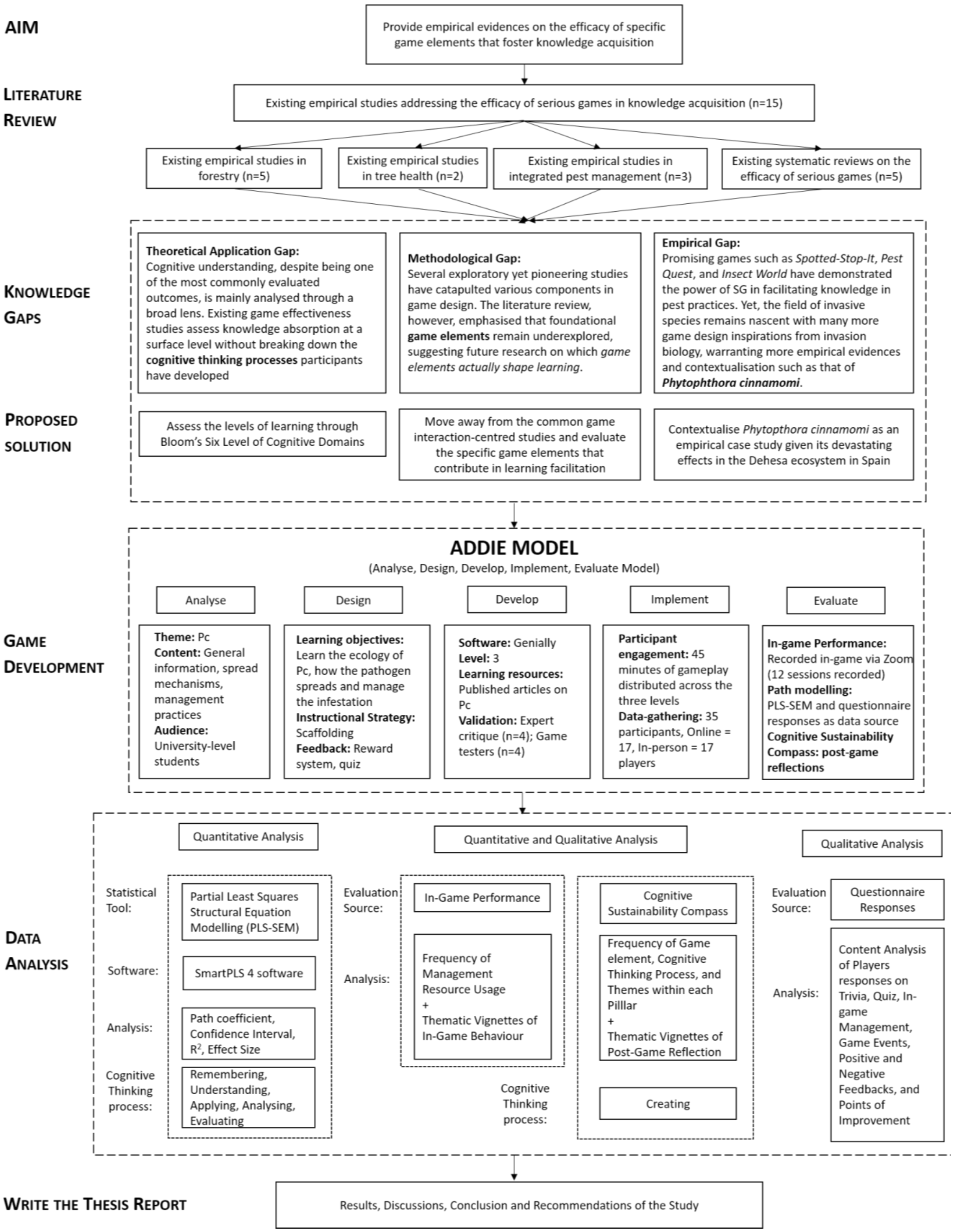


Figure 7. The research design of the study, detailing the literature review process, the game development following the ADDIE model, and the different analyses performed.

Figure 8. Some examples of players engaging with the card-sorting activity to demonstrate their sustainability reflections and create their own Cognitive Sustainability Compass.

4.6 Game Play

There are two modes of game play that were performed in the study, namely online and in-person game play ([Figure 10]). All players were provided with a two-minute game instruction material with audio and video support at least two days prior to their schedule. For both cases, the researcher first introduced the game inspiration of Silent Spread, the definition of SGs, and BCD. The discussion then proceeded with the basic instructions for Level 1 such as activating the game, selecting the game avatars, treating the infected trees, and player movement across the digital boards. Afterwards, the researcher sent the link of Silent Spread via Zoom chat for those who joined the online facilitation while the researcher used his own laptop to facilitate the in-person playing. All players then shared their screen and their game performance was recorded through the Zoom record function. A total of 12 game sessions were recorded, composed of 6 sessions for each gameplay mode. The total duration of each level is ten minutes, 12 minutes and 15 minutes for Levels 2 and 3, respectively. The assigned duration (or timer) on each level is arbitrary but still follows the scaffolding approach where the level duration accounts the increasing number of game elements (i.e. trivia, quizzes, and in-game management resources) as the game progresses.

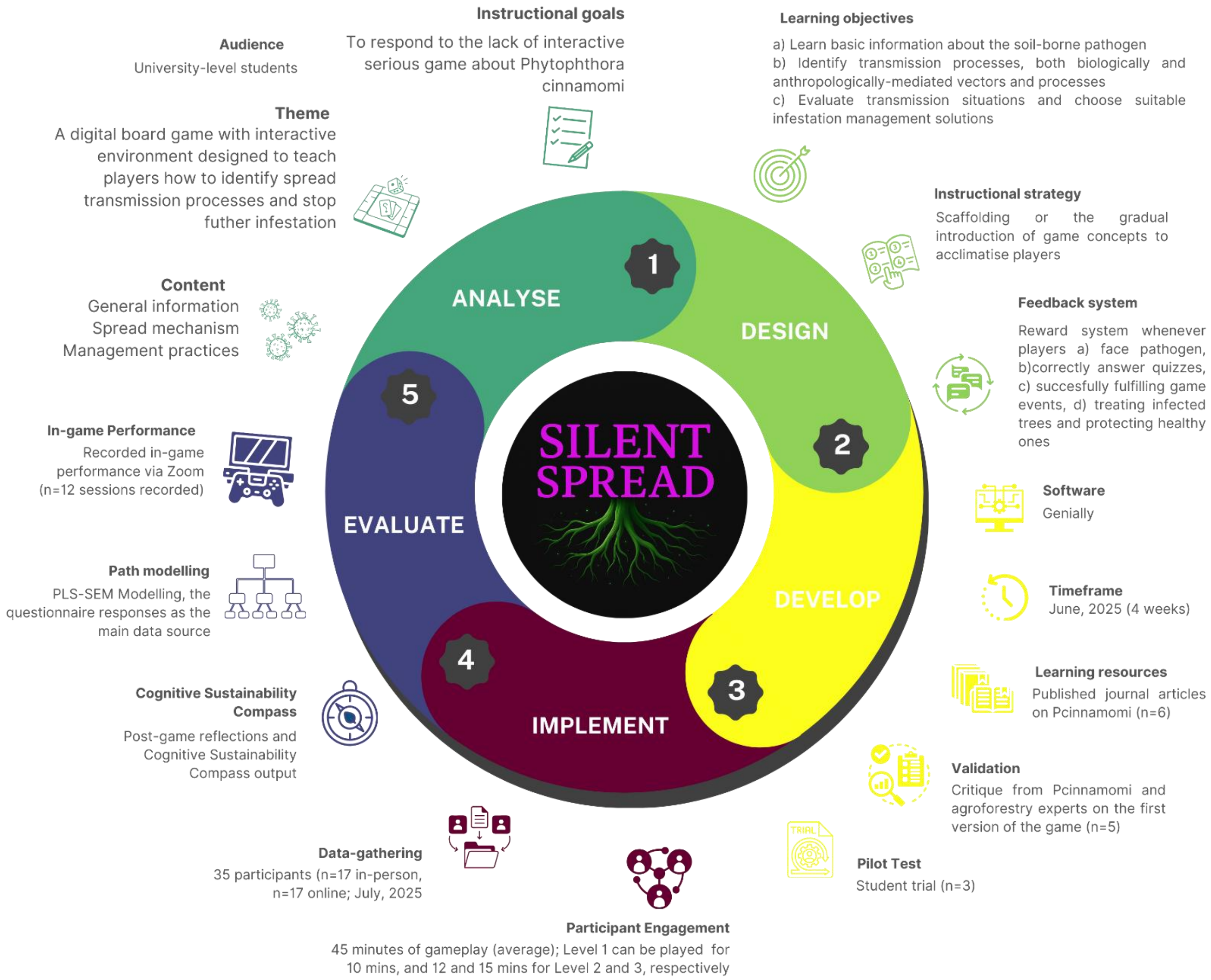


Figure 9. The ADDIE model demonstrating the key components of the game development following the five-phase approach.

Figure 10. Players participating through either in-person where two to three players access the game using the same laptop. Meanwhile, the online mode employs Zoom and facilitated by the researcher.

4.7 Statistical Tools

4.7.1 Structural Model

Before the quantitative analysis is discussed, it is imperative to explain the variables in the structural model. The exploratory nature of this research draws from BCD (Anderson & Krathwohl, 2001; Bloom, 1956) and results of the systematic review. The structural model (Figure 11) is designed to investigate how game elements contribute in shaping various cognitive thinking processes, addressing the theoretical application and methodological gaps of the study. The four elements investigated include a) trivia, b) quiz, c) in-game management, and d) game events constituting the exogenous constructs of the structural model. These constructs serve as the independent latent variables, "predicting and providing the point through which the variance or the causal relationship assessment initiates" (Hair, et al., 2022, p. 16). Being an exogenous entity in the model, these constructs are not explained by any other construct, meaning their variance is determined outside the structural model. Despite yet, exogenous constructs are critical in providing predictive power to explain the network of relationships. The study does not explicitly adopt predefined framework for the game elements, rather, their inclusion is grounded from the results and recommendations of existing literature on SG research, ensuring that the overall conceptual framework design is informed by scholarly evidence.

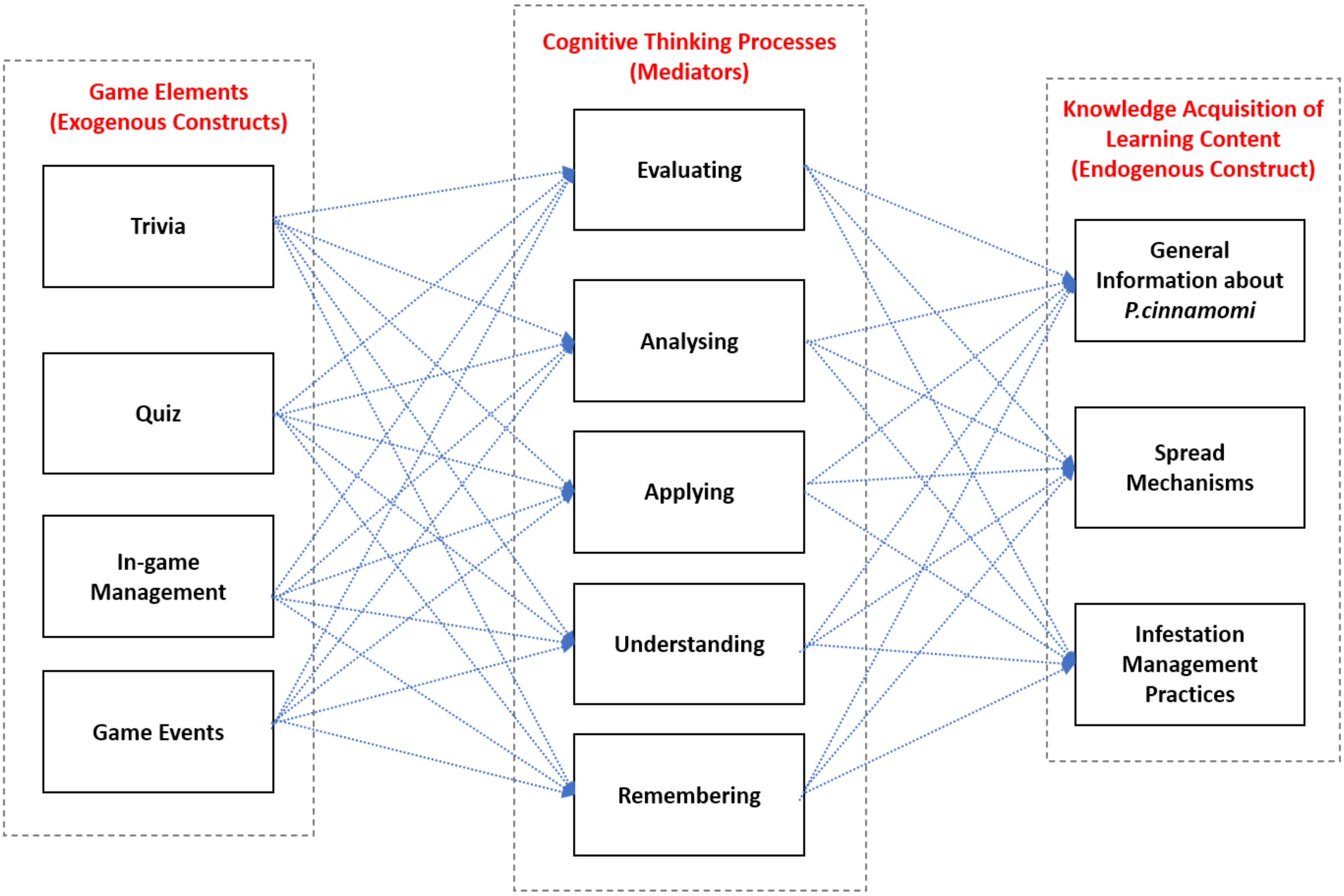


Figure 11. The conceptual framework of the study integrates the game elements as exogenous constructs, the five cognitive thinking processes serving as the mediators, and the intended learning content to properly contextualise Pc acts as the final endogenous construct. Source: Author's own interpretation inspired by the graphics of the game. Dashed lines represent the pathways to be tested using PLS-SEM.

The mediators of the model utilise the cognitive hierarchies, which include a) remembering, b) understanding, c) applying, d) analysing, and e) evaluating. It is worth reiterating that the highest thinking skill **'**creating' was not included in the structural model but will later be assessed outside the game play through the Cognitive Sustainability Compass. Mediators are special endogenous constructs bridging exogenous and the final endogenous constructs (Hair et al., 2022). They help explain how and why an effect occurs which is often assessed through indirect effects on PLS-SEM. In this study, specific indirect effects were used instead because they capture mediating processes, rather than assuming indirect effect.

Understanding the learning outcomes solely through the lens of cognitive domains does not cover the empirical gap of the study. This disables the opportunity to assess the content-specific knowledge gained which is a critical objective to properly contextualise *Pc*. Thus, learning content was embedded to explore three learning themes serving as the final endogenous constructs. Endogenous constructs are the dependent variables in the structural model. The learning content includes KA for a) general information about the pathogen, b) spread mechanisms, and c) management practices. Their variance is explained by the structural relationships and often assessed through measures such as coefficient of determination. These learning outputs (or learning content) are defined as the following:

(a) **General Information about the pathogen**. This theme includes the ecology of Pc such as its biological characteristics, the effects to tree mortality, history, and its impacts to the Dehesa's agricultural sector.

(b) **Spread mechanisms**. The learning output refers to the infestation mechanisms of the pathogen including both natural and human-mediated activities. These factors involve animal and human movement as vectors, and bioclimatic dimensions like rainfall, drought, surface water flow, and topography.

(c) **Management practices**. Infestation management practices, on the one hand, involves learning about the biological, mechanical, and chemical ways to stop the pathogen dispersal.

4.7.2 Quantitative Data Analysis Tool

The quantitative data collected was analysed using Partial Least Squares Structural Equation Modelling (PLS-SEM), a statistical tool often used in business, human resource, marketing, accounting, information systems, education and social science studies (Memon et al., 2021). PLS-SEM is a multivariate tool suitable for modelling relationships between observed variables by extracting latent structures (Vinzi & Russolillo, 2013). The statistical tool is well-suited for exploratory research, small population sizes, and models that include both formative and reflective constructs (Hair et al., 2021); research dimensions that all align with the current study. PLS-SEM's user-friendly visualisation is often praised by researchers, enabling the simultaneous analysis of relationships between observed and latent variables (Memon et al., 2021).

PLS-SEM merits as the most suitable tool for three reasons. Firstly, the statistical tool is particularly useful for exploratory data analysis, prediction, and cases where interpretability and variable reduction are vital components in the analysis. Since the specific SG design elements that facilitate KA remain heavily understudied, the exploratory power of PLS-SEM suits the overarching goals. Secondly, the path modelling integrated in PLS-SEM is particularly useful when complicated models are involved and the research attempts to understand how several dimensions are related. Given the objectives to operationalise several theories in the study (e.g. BCD), PLS-SEM can create a variable structure that silos the specific game elements effective in KA in relation to the pedagogical intent. This means PLS-SEM can simplify the complex and underexplored models in game features that are effective for content understanding. Lastly, this research does not aim to confirm any model, making PLS-SEM the robust method for the intended analysis. The tool being a variance-based, and not co-variance based make it fitting for the small sampling size of the study.

The researcher used SMARTPLS 4 software (Ringle, et al., 2023). The software provides advanced features such as a) bootstrapping procedures to test path coefficients, loadings, and outer weights, b) evaluation of model quality which includes composite reliability, average variance extracted, R^2 values, and effect sizes, and c) assessment of formative constructs through Variance Inflation Factor (VIF) diagnostics. Provided the exploratory nature of the study, PLS-SEM can handle the modest sample size (n=35) to test the hypothesised structural model. The software's bootstrapping function of 5 000 resamples served as the basis to determine the statistical significance of the model's path coefficients.

The data used in the analysis originated from the structured questionnaire (Annex F) administered after gameplay. Participants evaluated their experiential learning where interacting with the game elements acts as the main basis and whether key cognitive thinking processes were facilitated during the game. PLS-SEM begins by assessing the measurement model (Figure 12). This process entails performing single reliability testing using the square of the outer loading (Annex L). The square represents how much of the variation in an item is explained by the construct using the communality threshold 50% or higher. The process confirms whether each indicator contributes meaningful to its construct. Secondly, using bootstrapping method, the moder parameters are assessed through single reliability testing followed by internal consistency reliability. For the first reliability testing, the outer loadings' p-value is often examined while Cronbach's Alphas is used for the latter (Annex M). Cronbach's alpha examines whether multiple indicators jointly provide consistent outcomes. Moving forward, the convergent validity of the measurement model is performed to explain the variation of the indicators. From here, whether the set of indicator represents a strong single underlying construct that can later be assessed using Average Variance Extracted (Fornell & Larcker, 1981). Discriminant validity is subsequently examined using cross

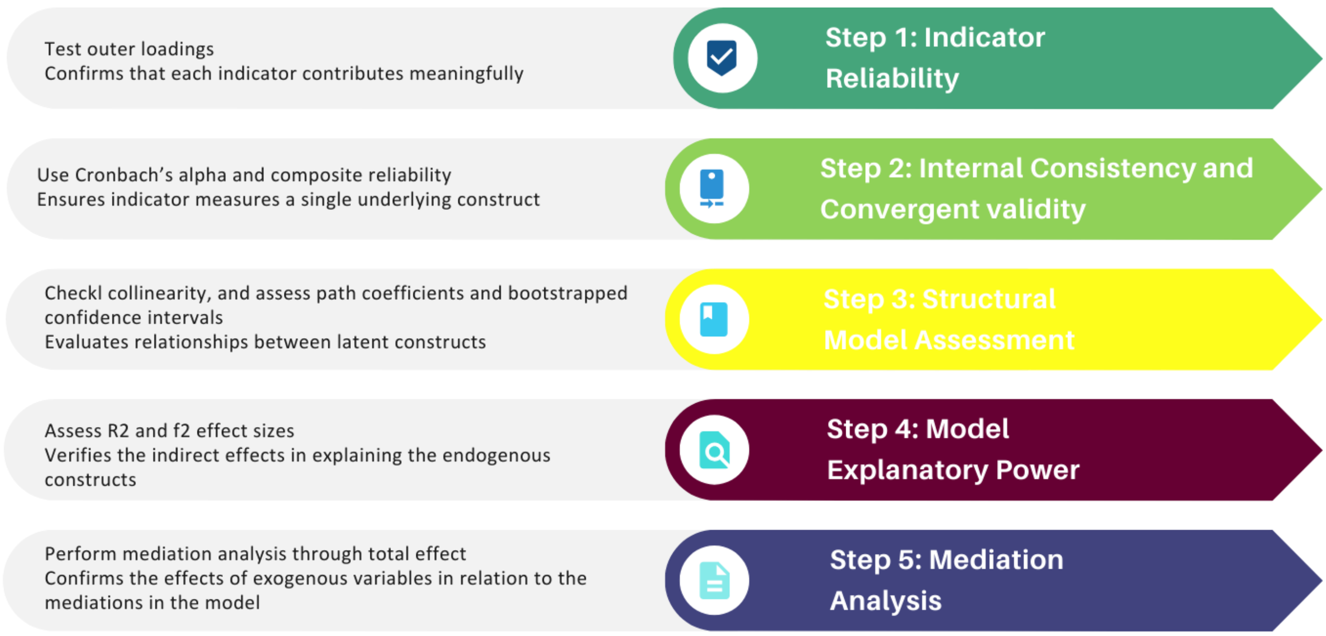


Figure 12. The flow of PLS-SEM. Source: Author's own graphics following Memon et al., 2021.

loadings, singling out how each construct is different from each other. The logic of the step was based on the idea that a construct may likely share more variance with its associated indicators than with any other construct (Annex M). Lastly, the Heterotrait-Monotrait (HTMT) score was examined as part of the discriminant validity (Annex N).

After checking the measurement model, the structural model was assessed. This phase commences with collinearity testing, where the variance inflation factor (VIF) is examined further to ensure that predictor constructs are not excessively correlated; values of 3 or below are recommended (Hair et al., 2019). Path coefficients and their boostrapped confidence intervals are then analysed to test the strength and relevance of the hypothesised relationship (or pathways). Lastly, the coefficient of determination using the R^2 value was inspected to explain the explanatory power of the game elements as the exogenous constructs. Effect size using f^2, on the one hand, assists in understanding through how an exogenous driver explains the endogenous constructs. It is also worth-mentioning that the mediation effect of the cognitive thinking processes was further analysed to determine how each mediator intervenes between the exogenous and endogenous constructs. Moderation effects were not detailed in the study due to the fact that there are no observed differences in between the groups despite the rich socio-demographic background the sampling unit holds. Majority of the discussion in the study details the result of the second phase of PLS-SEM.

Other structural equation modelling such as Covariance-Based SEM (CB-SEM) is not applicable to this research. This is primarily because the nature of the current study is exploratory rather than confirmatory, thereby, PLS-SEM fits the intended purpose. Moreover, the conceptual framework contains formative constructs (e.g. game elements) which CB-SEM is having difficulty analysing. Additionally, the modest use of small sample size (n= 35) is more suited for PLS-SEM as compared to CB-SEM which typically requires a larger population size.

4.7.3 Qualitative Data Analysis Tool

The qualitative strand of the study follows a content analysis approach. Content analysis is one of the two sub-components of systematic analysis (Neuendorf, 2018) alongside thematic approach. The research method involves sifting large volumes of data to discover and describe the focus of the participants' interpretation (Weber, 1990), enabling the examination of trends and patterns in the qualitative data (Stemler, 2001). Despite being critiqued as mere “word-frequency count” method, content analysis uses the word frequency to “identify words of potential interests thereby, strengthening the validity of the interferences being pulled out from the data” (Stemler, 2001, p. 1). The qualitative findings aim to complement the quantitative data, following a theory-driven approach supported by inductive theme generation. Three guiding frameworks were used, namely the Sustainability Compass (Sajeva et al., 2024), BCD (Anderson & Krathwohl, 2001; Bloom, 1956), and the literature that support the contribution of the four game elements. The coding matrix is composed of all reflections derived from the structured questionnaire (Annex F). Data was then organised into four dimensions: sustainability pillar, game element, cognitive thinking processes and illustrative quotes. Themes emerged by examining the commonly cited sustainability concepts across the three foundational pillars, particularly those that were emphasised by the respondents during the reflection session.

The process commences from reviewing the segmented raw data into analysable units of meaning such as the discussions made post-card-sorting activity. Secondly, these segments were neatly organised into deductive categories (i.e. pillar, elements, cognitive processes) as new sub-themes emerge. Third, frequency counts of game elements and thinking processes were also performed to support the prominence of the endogenous and exogenous constructs, with the intention to succinctly support the results from PLS-SEM. Lastly, chosen quotes during the discussion were selected to ensure grounded evidence from the players' own words and line of thinking.

Other systematic analyses such as thematic analysis, albeit applicable given its meaning-making approach, is not suited to bridge the quantitative and qualitative data. Since the study attempts to complement the qualitative data with the quantitative results, the strong focus on counting concept frequencies through content analysis offers a more logical approach as compared to thematic analysis, despite the two approaches capable of performing such task.

4.8 Addressing the Biases of the Study

Given that majority of the sampling unit belong to the academic circle of the researcher as a result of convenience sampling, personal biases were addressed in the study through standardised research process. The researcher used standardised process to inform the participants with the relevant information prior to playing the game. This include sharing the same email content (Annex J) accompanied with instructional videos about the game rules prior to game testing, implementing the same formal facilitation before, during, and after playing the game, and other standard data-gathering procedures such as the duration of gameplay, the list of sustainability cards the players explore for the qualitative reflection, and the same version and educational content of Silent Spread.

4.9 Informed Consent and Ethical Standards

The research adhered to ethical guidelines, particularly involving human participants. Participants did not receive any compensation and game testing was completely voluntary. Prior to playing the game, participants were introduced with relevant concepts such as SGs, the purpose of the study, and the framework being assessed (See Data-Gathering Presentation). All participants were given the opportunity to agree or disagree from recording the in-game performance and the option to withdraw from gameplay should inconveniences and discomfort arise. Moreover, the prepared questionnaire details the anonymity, purpose of data gathering, future usage of personal data, and encourages players to provide honest opinions and feedbacks post-gameplay. In the future, if the data gathered will be used to other purposes beyond the scope of the current research, participants will be provided with the pertinent details regarding the use of their personal data and their reflections from the game. The final output of the study will be shared with all the participants shortly after finishing the entire research. Additionally, the study acknowledges the use of artificial intelligence. The visualisation, graphics, and audio-support used in the game were assisted by Canva Pro. AI was also heavily used to learn about the accurate process in performing and analysing the results from PLS-SEM.

5. Results

The results are organised into three sections. First, the first section discusses the developed game, Silent Spread. The section explains the important game elements and features, demonstrating the accomplishment of the overarching goal of the study. In-game performances from recorded sessions were also detailed through three lenses, namely in-game quiz and management practice performance and thematic vignettes on players behaviour. Secondly, the result of cognitive modelling through PLS-SEM shows the empirical evidence, assessing game efficacy in facilitating KA. Lastly, the result of Cognitive Sustainability Compass activity supports the quantitative evidence provided by PLS-SEM and enumerates dominant linkages among the game elements, sustainability pillars, and cognitive knowledge dimensions.

5.1 Silent Spread as the Developed Serious Game

5.1.1 Game objectives

To achieve the overarching goal of the study and to illustrate the efficacy of SG in teaching *Pc*, Silent Spread was developed (Figure 13). Silent Spread is a digital board game designed to teach players the a) general information about *Pc*, b) the biophysical and human- and invertebrate-mediated factors that facilitate the spread of the root pathogen, and c) the management practices to stop the infestation to other vegetation. Silent Spread integrates three conceptual farms serving as the three levels (Figure 14). The game storyline is straightforward, matching the learning material intent. On each level, players have a) to face the root pathogens, activating the trivia, quizzes, game events as well as earning of resource items to stop infestation, and b) treat as many infected trees as possible. Participants can do these by strategically landing to the tiles where these special items are located. Players can advance to the next level after facing all the pathogens, and unlocking the resource items.

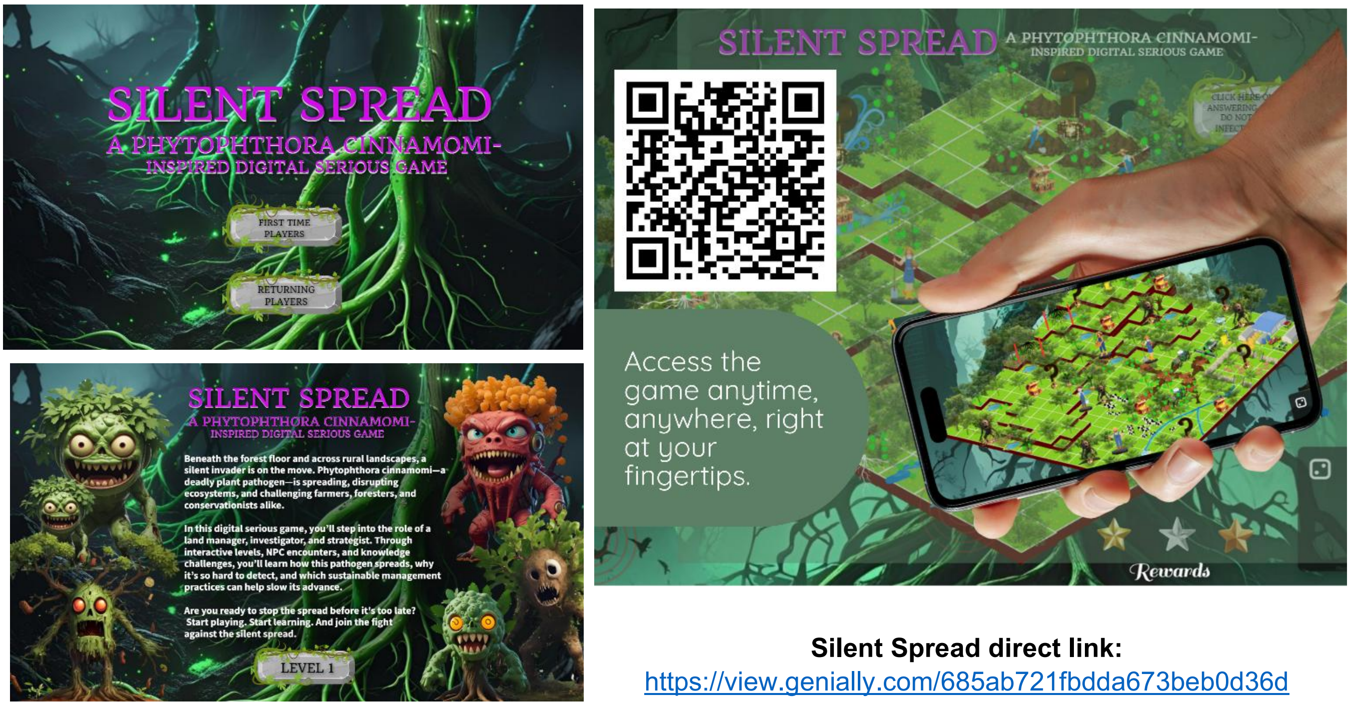


Figure 13. The landing page of Silent Spread briefly showing the creative narrative and role-play embedded in the game. The QR code which directs users to the game is also shown.

Figure 14. The three levels of the game demonstrating some of the management strategies made by the players. (Top) The player heavily used calcium fertiliser to manage the infestation along the edge of the farm. (Middle) Level 2 was cleared by the respondent by combining root barriers to protect healthy trees and calcium fertiliser to stop the further transmission on the other side of the river. (Bottom) The player makes use of all four management resources both as individual and integrated solutions.

5.1.2 Game levels

The three levels start from a simple farm typology which evolves into a larger and more complex landscape (Figure 16). Levels 1 and 2 have 8x8 tile configuration while Level 3 follows an 11x11 tile arrangement (Table 1). Level 1 begins from simple landscape typology with only oak trees and shrubs as vegetation. The second level introduces a water system and livestock, increasing the understanding of players about Dehesa ecosystems while farm house and warehouse, topography, and increased number of oak trees were added on the last level. Each level contains 10 characters players can choose from, potentially increasing their motivation to learn the materials (Gee, 2005). Avatar customisation is limited on the software used by the researcher, albeit, an effective game interaction to engage players using characters they see themselves in (Gonza´lez Gonza´lez & Blanco-Izquierdo, 2012; Gee, 2005). Despite the technology and budget constraint, allowing the players to choose from a range of diverse prepared avatars was made an option in the game. Once the level has been activated, the time limit also begins. Level 1 is set to finish within 10 minutes while Level 2 and 3 can be played for 12 and 15 minutes, respectively. The allotment of time limit is arbitrary so players can finish the game testing within 45 minutes taking into consideration factors such as game fatigue and overstimulation from information and graphics. Time, generally, can be considered as worthy opponent of players to win the game (Schmitz et al. 2015) and activate collaboration to clear the game. Moreover, each level contains resource items that game testers can use once they correctly answer the quizzes (Figure 16). The number of management resources players earn depend on the difficulty of the questions they cleared.

A Quest Log serves as marker showing how many more pathogens and resource items players need to unlock to advance to the next level (Figure 15). Players can also win different stars which include Gold, Silver, and Bronze corresponding to a point system. Gold star holds three points while Silver and Bronze are equivalent to two and one point, respectively. Every time participants obtain stars, they need to drag their winning to the Leaderboard. Earning these stars depends heavily on several game rules. For instance, using one resource item to stop the infestation enables a player to earn bronze and gold if they combine several solutions. Such reward system is tied to the learning outcome, particularly the ways how each resource item is used to treat infected trees and stop further infestation. Given the complexity of scoring matrix, a Rewards system that can be viewed at any time is available in the game, helping players check the correct combination of management solutions. The quest log and leaderboards are some examples of reward systems that enhance user engagement and foster behaviour (Radziszweski et al. 2021). Through the leaderboard, players can instantly know the competitive standing of their opponents while earning the stars acting as quick in-game feedback; two game components that are proven to facilitate learning (Cheng et al., 2015). The three levels are arranged in 3D axonometric visual representation and supported by audio and text. The graphics and audio were generated using the AI support tool on Canva through the AI Magic Media and AI Voice functionalities. The game environment and graphics are designed with realistically looking interface as much as possible and complex yet digestible enough even for high school students following the recommendations of several studies (i.e. Baranowski et al., 2011; Byun & Loh, 2015). A certain degree of in-game abstraction was applied since not all game components can be accurately represented in digital SG (Ravyse et al., 2017; Hong et al., 2013). Careful abstraction mainly involves the representation of landscape elements (e.g oak trees, topography, water system). Such game conceptualisation facilitates pedagogical delivery of topics such as spread mechanisms based on biophysical factors and other human- and invertebrate-mediated infestation, and providing context in game events like asking players to develop solution so the pathogen will not cross the other side of the water system. Five pedagogical experts in Pc were consulted to verify the in-game abstraction implemented in Silent Spread.

Figure 15. Game elements and other features that assist players in navigating each level.

5.1.3 Scaffolding approach

The disproportionate distribution of the elements (Table 1) is justified by the scaffolding approach used to develop the game. Scaffolding promotes a gradual introduction of levels difficulty and practice levels so players can acclimatise to the game's interfaces (Ha¨ma¨la¨inen 2011). The scaffolding approach is particularly useful in providing gradual instructions on how to use the in-game management resource (e.g. calcium fertiliser, root barriers, etc), and win rewards by playing the randomised game events, facing the pathogens, and answering quizzes. Farm typology on each level also evolves, introducing more farm elements (e.g. grazing animals, waterways, farm equipment) to the players as the game progresses.

Table 1. Summary of Game Features on each Level

Level	Time Limit	Tile	Landscape Description	Cognitive Process Being Developed through Quiz; Learning Content	Trivia	Quiz	In-Game Management Resource	Game Event
1 	10	8x8	Primarily populated with oak trees	Remembering, Understanding; General information	3	5	1	1
2 	12	8x8	Apart from oak trees, water way system and livestock such as Iberian pigs and cows are present	Applying, Analysing; Spread mechanisms, Management practices	4	6	2	1
3 	15	11x11	Increased number of oak trees, and a farm house and warehouse are introduced	Analysing, Evaluating; Spread mechanisms, Management practices	6	11	4	8

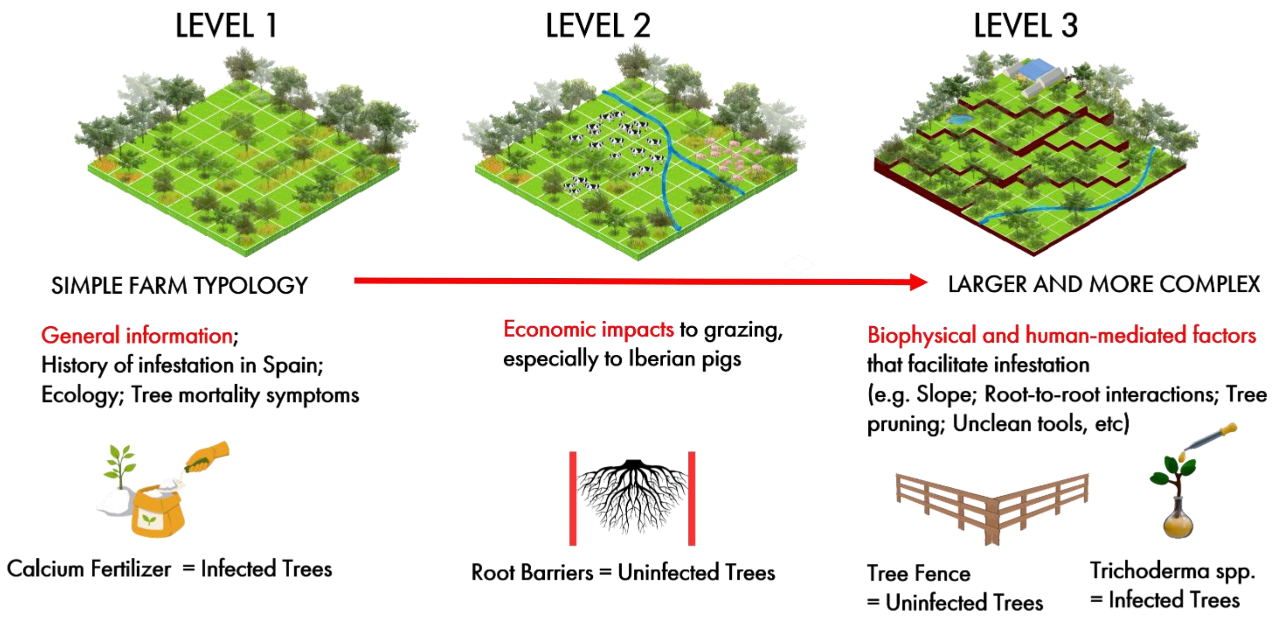


Figure 16. The three levels of the game which starts from a simple farm typology and evolves into larger and more complex landscape.

Moreover, the pedagogical content of the three levels is divided thematically (Figure 16). Level 1 discusses the general information of the pathogen, detailing the history of its infestation in Spain, and basic ecology such as tree mortality symptoms. The second level jumps to the economic impacts of pathogen infestation on grazing, particularly in Iberian pigs. Economic implications of reduced acorn production due to oak tree mortality rates and poor production level were emphasised on the level, gradually moving from basic ecology to economics of *Pc* infestation. The last level teaches the biophysical factors, and human-assisted activities and influence of invertebrates in facilitating pathogen transmission. Three infestation mechanisms were introduced that are apparent in the Dehesa ecosystem. These include root-to-root transmission, surface and sub-surface water flow, and dispersal through human and invertebrate movement. Table 1 details the distinct characteristics of each level.

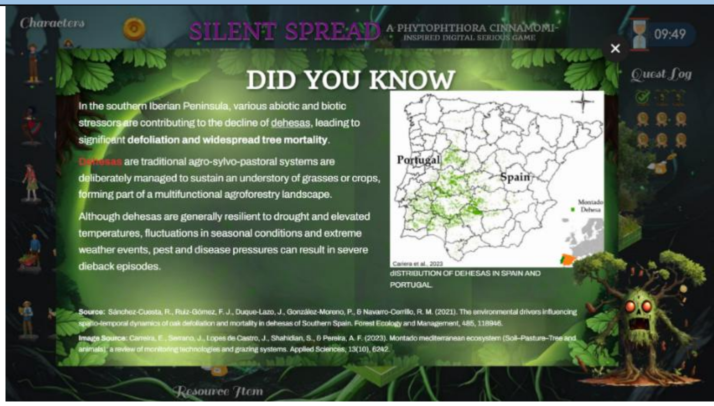
Additionally, the introduction of four infestation practices was introduced on each level. For instance, calcium fertilizers, being the most common and cheapest solution, is showcased on Level 1. Level 2 encourages players to use two resource items, namely calcium fertiliser and root barrier. On this level, players begin to strategize combination of solutions since the two can be used for infected and healthy trees. Level 3 allows players to use all four management solutions guided by a scoring matrix to increase motivation. These resources are earned by answering correctly the quizzes or successfully fulfilling the tasks mentioned in game events. Table 4 provides the summary of management combinations performed by players.

5.1.4 Game Elements

Table 2 summarises the four game elements, describing the nature and providing examples to better illustrate Silent Spread as players navigate the game and acclimatise with the features.

Table 2. Summary of Game Elements and Illustrative Examples

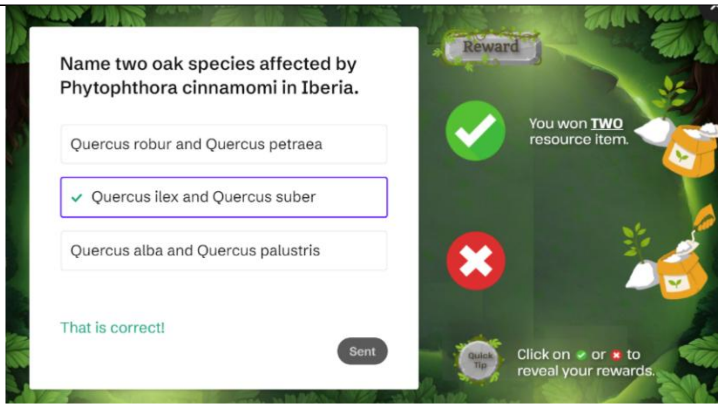
<table>
<tr><th>Game Element</th><th>Examples</th></tr>
<tr><td>(a)Trivia. The trivia can be explored once players perform two things in the game; facing the pathogen and unlocking new resource item such as the management practices. Trivia cards are evidence-based and properly cited. Some cards would contain supporting images, maps, and or game instructions.</td><td>



Note 1. Example of a game trivia supported by map as visual aid.</td></tr>
<tr><td></td><td>

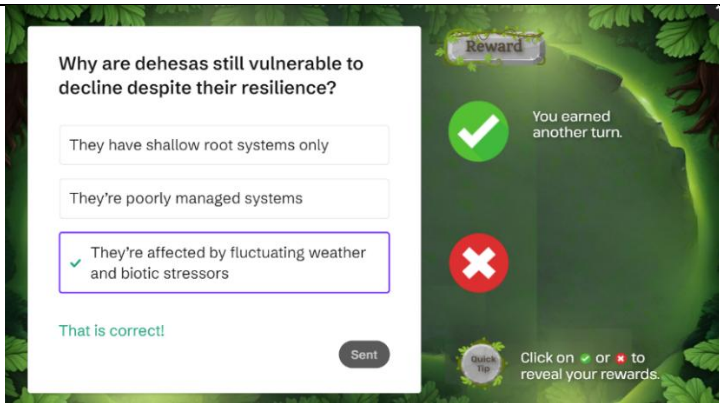
Note 2. Example of a trivia about calcium fertiliser, one of the four infestation solutions and explaining how to use the item in the game.</td></tr>
<tr><td>(b) Quiz. All quizzes are multiple choice. Once players choose their answer, they must hit the Send button to check their response. Participants could win stars, earn a new turn, steal stars from opponents, and win infestation management resources if they answer correctly. Punishment for wrong answers include losing one to two turns, and returning the stars players earned.

Quizzes are also designed in such a way that questions sharpen different cognitive process on each level. Specifically, questions on Level 1 foster remembering and understanding as cognitive process while Level 2 captures applying and analysing thinking skills. Level 3 embodies questions that cover applying, analysing, and evaluating. To reiterate, the highest thinking skill “creating” is not included in the association because playing for a</td><td>

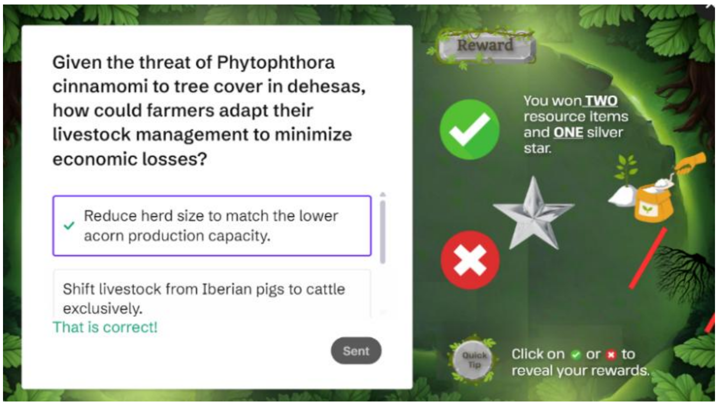


Note 3. Example of question that captures the cognitive skill 'remembering'. Here once players correctly answer the quiz, they could win resource items to stop the on-going farm infestation.</td></tr>
</table>

short period of time makes capturing this cognitive process difficult.



Note 4. Example of a quiz capturing the process 'understanding'.



Note 5. Example of a quiz question that covers the process 'applying'. The image also shows the player won two resource items, and one silver star.

(c) In-game management. Each level provides details about the management solutions to stop further infestation. Level 1 introduces calcium fertiliser which can be used for infected trees in the game. The solution is the most commonly used management in Spain given its low cost (Serrano et al., 2012), hence, being introduced on the first level. Level 2 discusses root barriers, a management resource effective for long-term protection (Dunstan et al., 2010). The last level showcases two management practices, namely fence and Trichoderma spp as mechanical and biological solutions, respectively. Erecting fence generally acts as effective obstacles for livestock and human movement which are crucial vectors during active infestation stage (Cardillo et al., 2012). On Levels 2 and 3, players combine solutions, implementing integrated strategies to stop the farm infestation. For instance, they can combine solutions that both

Note 6. Example of a trivia card which discusses the solution Trichoderma spp. application.

Note 7. The image demonstrates the solution done by Player 25 who is affected by a game event. The player was tasked to stop the infestation from crossing on the side of the river. The game first introduced the actions done by Fitzgerald National Park to stop the similar problem, serving as the inspiration before activating the game event. The root barrier being intentionally used for uninfected trees was heavily placed to protect the trees while calcium fertilisers were applied to infection sites.

Note 8. Here Player 28 makes use of all four management solutions on Level 3, creating several combinations of practices such as the integration of fence and root barriers, and fence and calcium fertilisers.

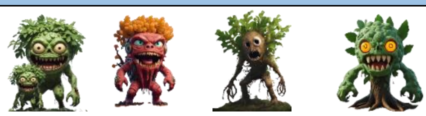
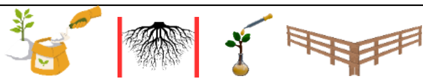
Note 9. Player 24 successfully combined and used management solutions individually, showing creative thinking in managing the farm infestation

(d) **Game events.** Game events are activated randomly on the game. They can be played by individual or groups depending on the effects of the event. Some examples of game events require players to use unlimited number of resources to stop the infestation, for instance, avoiding the further spread of pathogen on the other side of the river. Another game event makes one player to become a pathogen vector. Here affected players must put a Pc icon on every tile he/she passes by.

Note 10. This demonstrates how Player 21 was affected by game event wherein all the paths he/she walks become an infestation site.

Note 11. The first game event on Level 1 allowing players to use unlimited resources to treat the newly activated infestation site. Here the players are just acclimatising from managing the infestation, hence, an unlimited resource use is permitted.

Table 3. Summary of Game Element Representation in the Game

Game Elements	Representation
Trivia	
Quiz	
In-game management	
Game Events	

5.2.1 Socio-demographic profile

The game testers were comprised of a relatively diverse group, albeit some categories are prominently represented (Figure 17). Out of the 35 respondents, majority fell within the young adult range, particularly in the early mid-twenties (25-30 years old) while only a small fraction of players belongs to younger and older group. Gender distribution was balanced where men represented nearly equal the female participants. Most players are currently pursuing Master's degree and only a small subset were undertaking doctoral studies. Meanwhile, majority were originally from the Philippines (n=11), followed by USA and Spain (n=4). The rest of the countries have at least one representative (Figure 18).

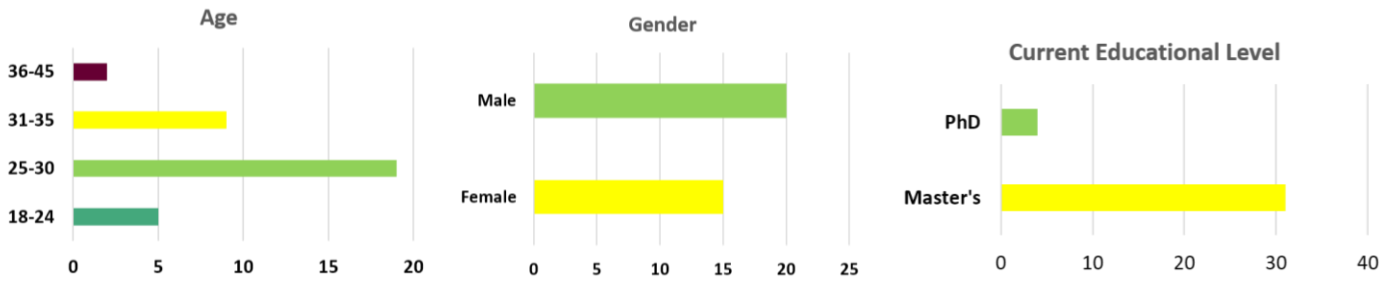


Figure 17 shows the summary of socio-demographic profile of the respondents, showing the age distribution, gender, and current educational level participants are pursuing.

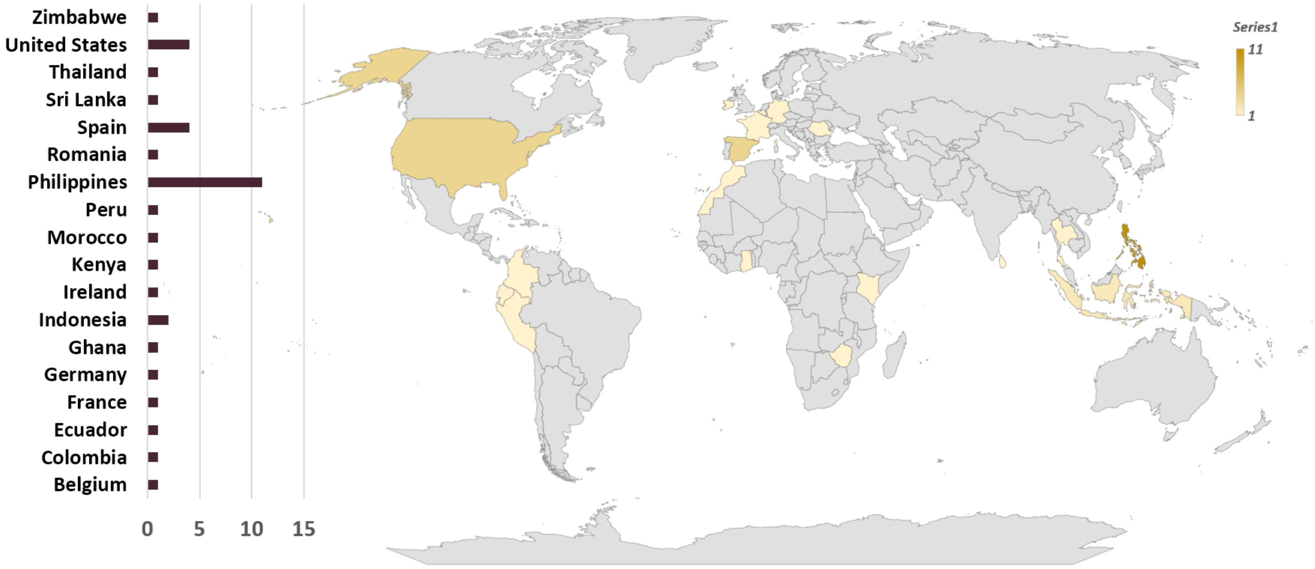


Figure 18. Global distribution map showing the representation of players (n=35) across the globe. The colour represents the distribution of players from the country.

In terms of prior formal courses taken, and work and internship experiences, the distribution among the participants vary (Figure 19). A large proportion of players has attended courses related to Sustainable Development, Environmental Science, and Ecology. Sustainable Development emerged as the most common classes attended by the group while Invasion biology had the fewest exposure to the subject matter. Notably, Forestry and IPM also fall on the lower course exposure, a critical observation since many of the participants have only encountered topics such as tree mortality and *Pc* through the game rather than prior formal education and training.

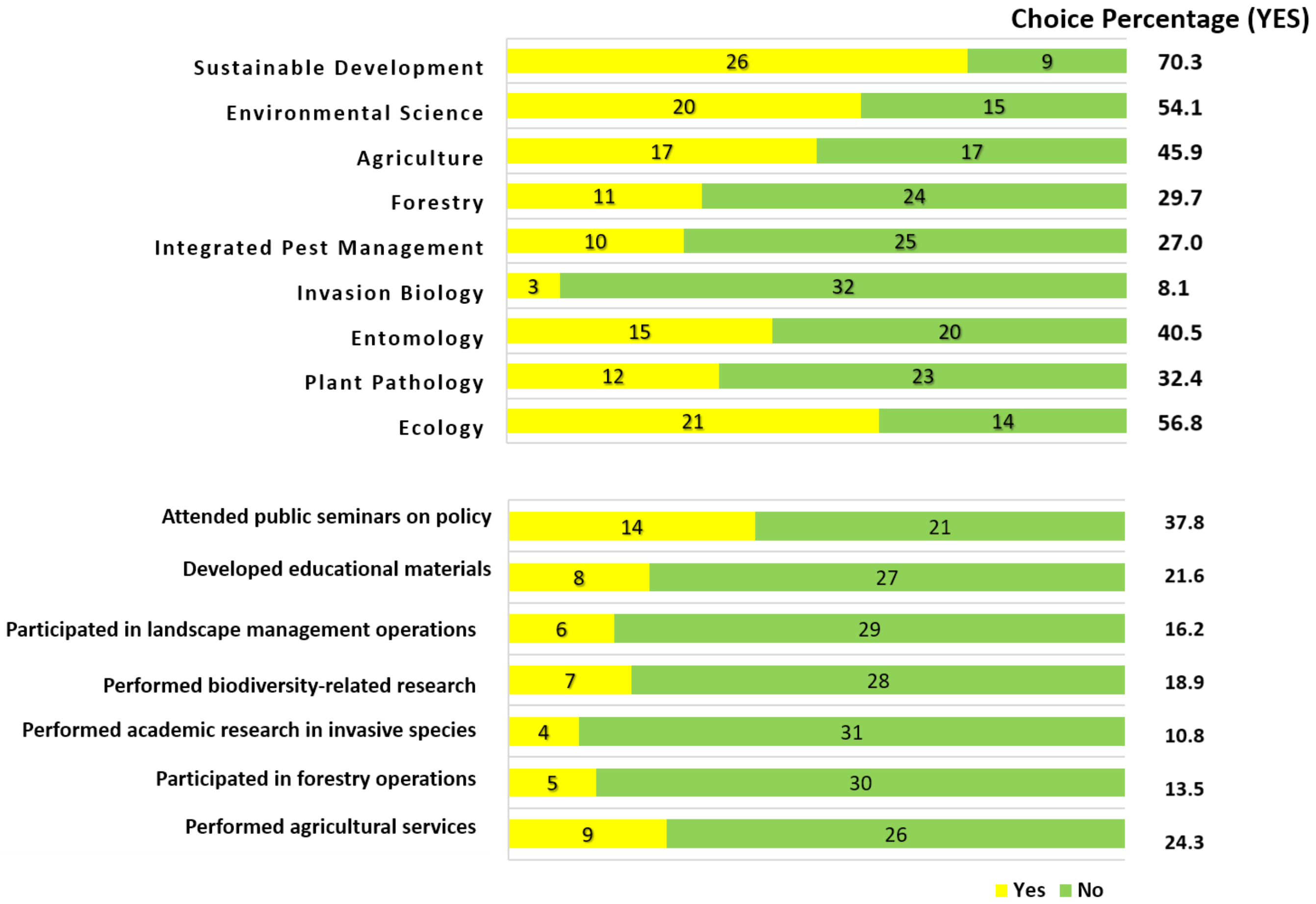


Figure 19 summarises the formal courses taken by participants and their relevant prior work or internship experiences across environment-related disciplines.

Majority of the participants have previously attended public seminars or public discussions on invasive species and climate-related topics (Figure 19). Players also have prior experience in performing agricultural extension services such as farm advisory, and had experience in developing educational materials. In contrast, fewer participants reported direct involvement in forestry operations and performing academic research on invasive species. Such limited exposure to these topics is of particular relevance because the distribution results signify the game as the first opportunities for players to learn about pathogen infestation and its connection to forestry-related production.

The knowledge of the players about *Pc* prior to playing the game falls in universally low category with 66% of players indicated "none at all" (Figure 20). Results demonstrate that familiarity with IPM and sustainability pillars was more widespread. Less than half of the participants mentioned they have little to no prior exposure while 25-30% rated themselves as somewhat acquainted. The remaining third remarked they are fairly knowledgeable about the two topics. Moreover, participants showed fairly strong literacy in digital or analogue board games. Participation in engaging with educational games prior to playing Silent Spread was low, with 72% reporting they have no exposure to fairly little experience.

It is worth-mentioning that cross tabulation was performed across groups. However, data reveals that despite the rich socio-demographic profile, there is no statistically significant association within the groups. The statistical analyses involved groups based on gender, age groups, current educational level, as well as history of courses taken at a formal institution and work experience, and their prior knowledge and experience. The absence of significant group differences suggest that socio-demographic profiles will unlikely act as confounding factors in the PLS-SEM, concretising the need to laser focus the relationship modelling among game elements, and cognitive thinking processes.

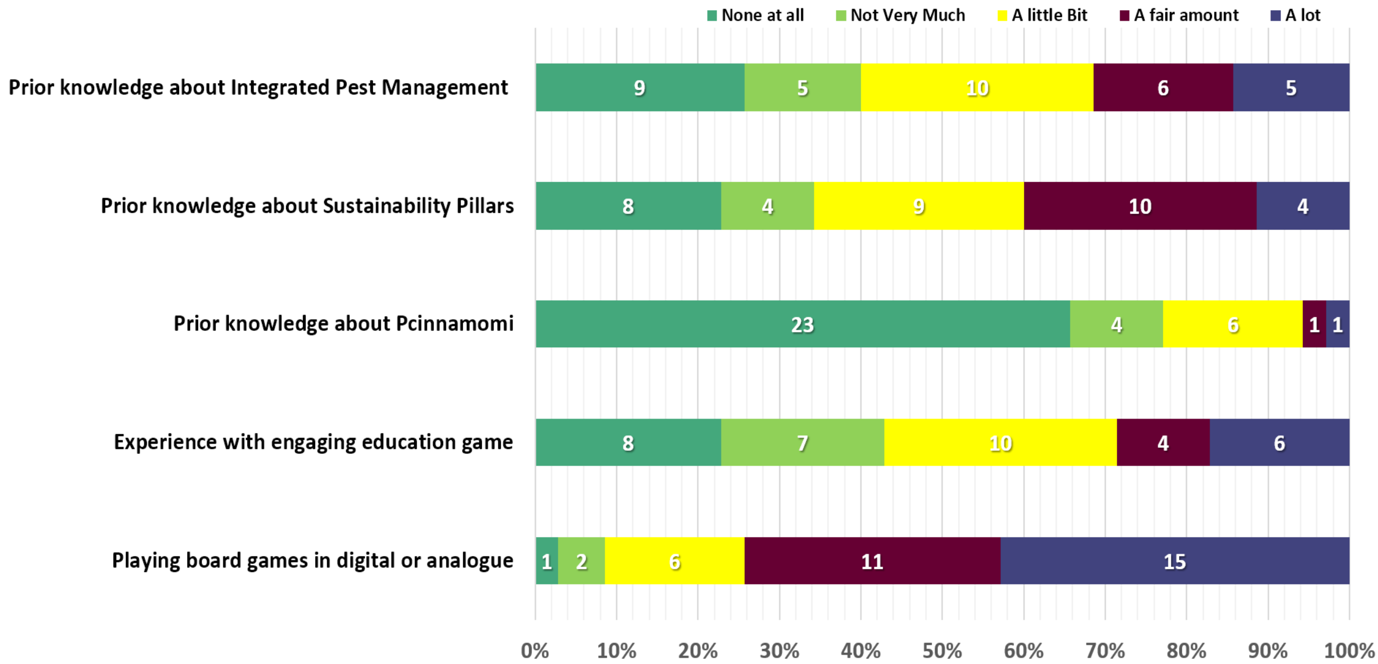


Figure 20 illustrates the prior knowledge and experience of the players before engaging with Silent Spread.

5.2.2 Player Experience

Overall, players responded positively to Silent Spread (Figure 21). Roughly two-thirds of the participants agreed or strongly agreed they were satisfied with the overall experience. A similar proportion indicated Silent spread met their learning needs while nearly two-thirds mentioned they will recommend the game to others to learn more about *Pc*. In terms of engagement, more than half of the game testers felt encouraged to learn more about pathogens, highly associating their complete engagement while playing. Nearly three-quarters noted that they are agreeing or strongly agreeing to such. In addition, over half of the participants described Silent Spread was visually stimulating.

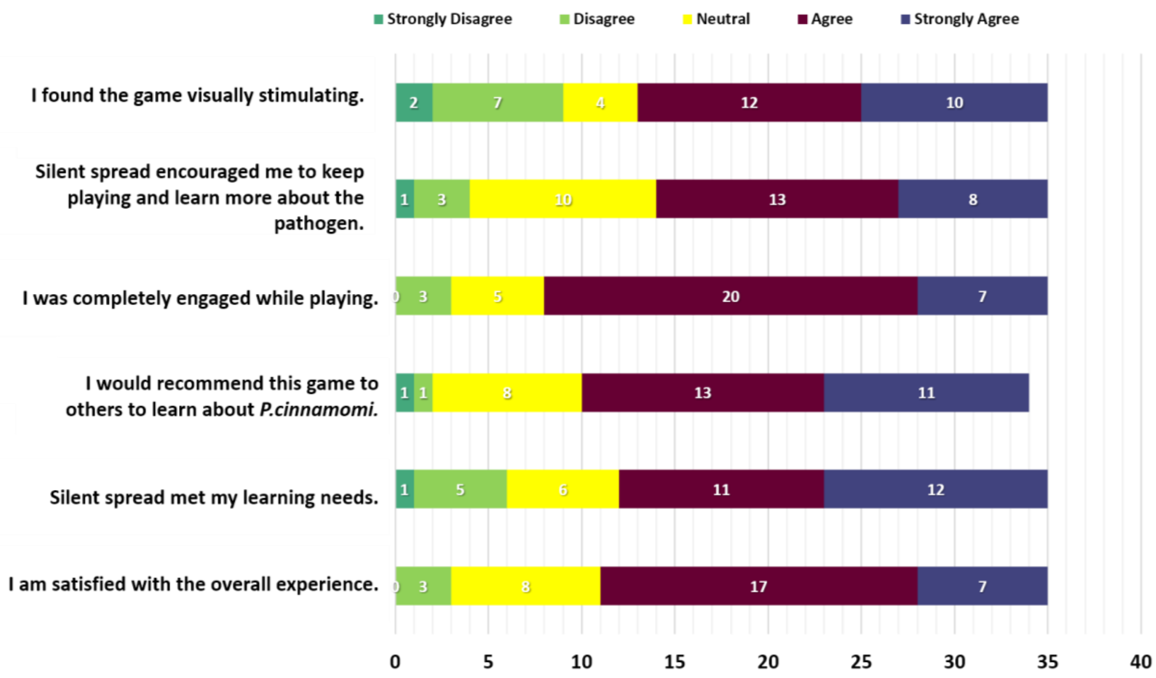


Figure 21 outlines the distribution of overall experience of the participants, capturing indicators such as visual stimulation, meeting learning needs, and the intent to recommend to others.

5.2.3 In-Game Performance in terms of Infestation Management Implementation

In-game analytics record the performance of players and to some extent the level of commitment in fulfilling game objectives, particularly in correctly answering the quizzes and creatively using the management practices. A total of 12 in-game performances were recorded and analysed. Both single and multiple player game sessions have 6 recordings on each.

Results reveal that calcium fertiliser was used 56 times on Level 1 which increased slightly on Level 2 with 59 implementation occurrences (Table 4). Root barriers (n = 49) were also widely explored by players on Level 2 and a handful attempted to combine calcium fertilisers and root barriers (n = 10). By Level 3, calcium fertiliser still remained the most prominent solution (n = 34), despite the decline from previous level. This decreasing observation was also exemplified by root barrier implementation. Meanwhile, fence (n= 10) was favoured twice as much as the Trichoderma spp. application (n = 10). The third level also offers more integrated solution to treat infected trees. The most frequent combinations were fence and Trichoderma application (n=7). The integration of calcium fertiliser and fence was done four times. Calcium fertiliser and root barrier, and calcium fertiliser combined with *Trichoderma spp* were used twice while combining root barrier and *Trichoderma* was only implemented once. Notably, combining root barrier and fence was entirely unused in the game. Table 4 visually summarises the usage of each management solution on each level.

Table 4. Summary of Management Solution Usage Frequency

Level 1			Level 2			Level 3		
Representation	Solution	Usage Freq.	Representation	Solution	Usage Freq.	Representation	Solution	Usage Freq.
	Calcium fertiliser	56		Calcium fertiliser	59		Calcium fertiliser	34
				Root barrier	49		Root barrier	13
				Calcium fertiliser + Root Barrier	10		Fence	10
							Trichoderma application	5
							Calcium fertiliser + Root Barrier	2
							Calcium fertiliser + Fence	4
							Calcium fertiliser + Trichoderma application	2
							Root barrier + fence	0
							Root barrier + Trichoderma	1
							Fence + Trichoderma	7

5.2.4 In-game Performance in terms of Answering Quizzes

The cognitive thinking process was also analysed through the 12 in-game recordings (Figure 22). Results demonstrate that questions embedded in quizzes designed to capture applying as the cognitive process achieved the highest accuracy, with only 1 incorrect response out of 29. Evaluating ranked second closely followed by understanding. In cognitive process remembering, the players' performance was mixed: 14 responses were accurate whereas 7 mistakes were accounted. The similar pattern was observed for analysing where only over half of the questions were successfully answered. Generally, while the results showed that successful responses outnumbered errors, applying, evaluating and understanding yielded highest level of accuracy but 'Remembering', particularly Analysing presented difficulty among players.

Lastly, players' performance was examined in relation to the learning content of Silent Spread (Figure 22). Results illustrate that respondents tested the highest accuracy in general information category with 36 out of 39 questions. Players' performance in thematic content spread mechanism is slightly higher than management practices. Twenty-two questions (85%) were cleared successfully out of 26 for questions under the management practice category. Meanwhile, questions under spread mechanisms as learning output ranked last in terms of players' performance in answering quizzes.

Taken together the earlier analyses of the three cognitive dimensions, the findings make clear that successful responses from quizzes predominated the recorded errors. Notably, the frequency of mistakes increases as questions move up toward middle-order thinking skills, then decreases again as players navigate quizzes with higher-order cognitive demands (Figure 22). For cognitive processes, players performed well in higher-order skills like applying and evaluating while difficulty is evident in analysing tasks. Learning content has shown that respondents answered well questions regarding the general information about *Pc* and spread mechanisms while there is still a correct-to-wrong ratio exhibited in management practices-related items, despite ranking the lowest.

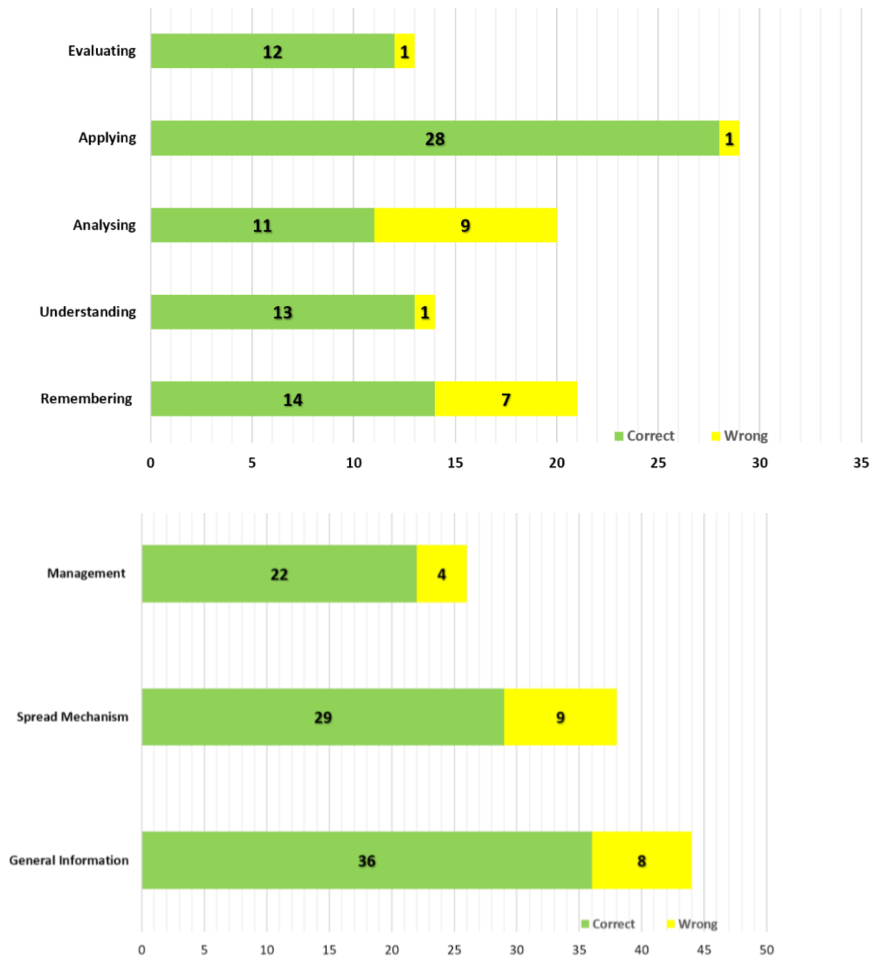


Figure 22 consolidates the distribution of player responses from in-game quizzes, detailing the performance on each cognitive thinking processes (top panel) and across the three learning outcomes (bottom panel).

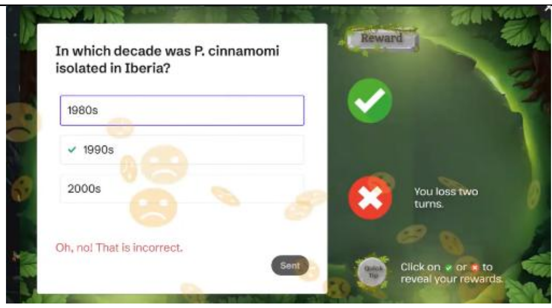
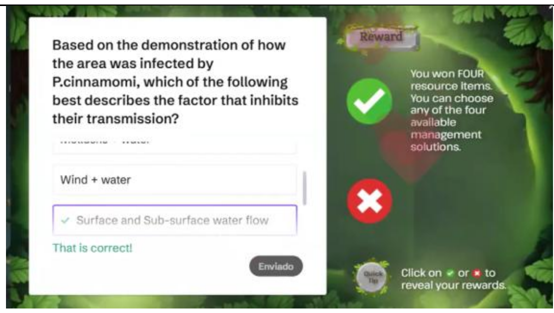
5.2.5 In-game Performance in terms of Recurring Player Behaviour

Beyond quantitatively analysing the three cognitive in-game performances, the recurring behaviours of players, particularly detailing infestation resource usage and cognitive performances were investigated (Table 5). A clear pattern emerges that players grasped the basic rules of the game which is to treat infected trees using resource items. Some players take advantage of game events where they have unlimited resources to stop the infestation even treating those unintended areas beyond the event instructions. Player 25 demonstrated mastery of application by correctly installing root barriers for healthy trees and used calcium fertilisers to infected ones. Not only the player confidently implemented combined solutions to appropriate scenario but also maximised the opportunity to treat all infected trees that are far from the river. Player 25 added, “I could just protect all of them, not very efficient but at least [all trees have been treated]”. Findings also indicate that players prioritised winning rewards than treating infected oaks. For instance, respondents would instantly combine resources in every opportunity they get fully knowing that gold stars wait for their strategic decision despite only treating one tree. However, using the similar two management items can earn them two bronzes by treating two infected trees. In the end, one gold and two bronze stars would be counted as two points based on game mechanics. Player 31 remarked, “Earning gold in comparison to covering a larger area, I will choose the three bronzes instead to save more trees.”

Fortifying the quantitative evidence of players’ performance in relevance to cognitive processes (Figure 22), Player 7 and 8 successfully cleared higher-order thinking quiz items but struggled with basic fact recall. During the game session, the two players applied the acorn-Iberian pig trade off knowledge accurately but when asked about the infestation history of *Pc* in Iberia, they faced the consequence for answering wrong. One player asked, “Why are the rules like this [with consequences, time limit, and other barriers]?”, showing frustration from committing mistake. Furthermore, one particular game event contributed to players struggle with analytical tasks. For example, Level 3 introduces a treasure chest that deploys spread mechanisms (e.g. root-to-root transmission, surface and subsurface water flow transmission, etc.). Players had difficulty analysing the transmission demonstration, Player 29 even said, “I think we did not see enough what happened.” Interestingly, several players found this game mechanics intellectually stimulating such as the remarks of Player 30 asking, “Can I still move to the treasure chest even if the time [limit] is up? I want to see the others.” Another player mentioned in the survey, “I liked how we had to think about the animation (referring to treasure chest demonstration) and depict them in the quiz.”

Behaviours that emerged illustrate motivation through reward system, game challenges, and cognitive competence. Such recurring in-game actions closely align with the quantitative evidence presented (Figure 22). For instance, Player 25’s mastery of implementing solutions mirrors accuracy in navigating applying and evaluating’ s strong accuracy in clearing embedded quizzes. Moreover, the weak basic fact recall yet strong analytical power of Player 7 and 8 corresponds with the same findings on remembering-analysing association demonstrated in Figure 22. In connection with this, the reported difficulties in analysing transmission pathways are congruent with spread mechanism being the most challenging learning content. Overall, the behavioural patterns support the quantitative data from in-game quiz performance, steadily demonstrating that players can readily apply their knowledge and evaluate situations through the content absorption. Ultimately, difficulty in factual recall, conceptual understanding, and complex analytical reasoning emerged.

Table 5. Thematic Vignettes of Players' In-game Behaviour

Theme	Illustrative Case	Cognitive Process; Learning content	In-game Representation
Mastery of Application	Player 25 demonstrated mastery in using root barriers and calcium fertilisers during a game event. The event challenged the player to stop the Pc infestation from crossing on the other side of the river. Root barriers were correctly installed for uninfected trees, protecting the tree roots from possible infestation. Meanwhile, calcium fertilisers were applied to all infected trees that are close by the river. **Player confidently used the correct solution to appropriate infestation scenario.**	**Applying;** **Management practices**	 *Note 1. Player 25's intelligent use of two solutions to stop the spread across the other side of the river.*
Strong comprehension but Limited recall	Player 7 and 8 through a multiple player game session showed strong performance in answering quizzes designed to evaluate and apply the knowledge they gained to conceptual situations such as the trade-off between acorn production decline and maintaining of Iberian pig production in Level 2. Despite players demonstrating strong analysis of conceptual cases, Player 7 and 8 made errors in remembering facts on the first level. **Here players demonstrated high understanding but weaker recall about *Pc*.**	**Applying;** **Management practices**	 *Note 2.. Players 7 and 8, despite collaborating on the question, failed to answer basic fact recall about the pathogen's history.*
Struggles with Analytical Reasoning	Many players struggled with analytical reasoning. In Level 3, treasure boxes unfold spread mechanism followed by a question asking players to identify the factors that facilitate the transmission. For instance, this specific question was explored 10 times but only received 2 correct responses and 8 errors. Some	**Analysing;** **Spread mechanisms**	 *Note 3. Players found analytical questions challenging about the pathogen's spread mechanism.*

	found this task as one of the most entertaining parts of the game but many found this game mechanics confusing and hard to digest.		
Prioritisation on Reward System than Treating more Infected trees	Many players prioritised earning high point stars (e.g. gold over bronze) than treating many infected trees. For instance, if a player earned two resource items, (e.g. calcium fertiliser and root barrier), he/she can combine them on one tile and would earn a gold star *but* would only treat one infected tree. In contrast, players can use both the earned resource items to treat two infected trees and win two bronze stars which are still equivalent to two points. One gold and two bronze stars are, in the end, will still get counted as two points, but **players prioritised implementing solutions that would earn them high-value reward.**	**Applying;** **Management practices**	 *Note 4. Players prefer to gain more gold stars than saving more trees.*  *Note 5. Here player treats more trees instead of winning the higher rewards.*

5.2.6 Complementary In-game Performances

Weaving together the three stands of analyses, in-game performance in quizzes, the use of management resources, and behavioural vignettes, results demonstrate a coherent picture of players' cognitive engagement. Performance in quizzes (Figure 22) shows that players excelled from middle- to higher-order cognitive processes, but struggled with remembering and analysing. Game testers when confronted with complex content on pathogen spread mechanisms struggled both in quiz performance supported by captured conversations during game play (5.2.5, i.e. Player 29 and 30). Similarly, the observation on the complex manifestation of thinking processes was further reinforced by behaviours; participants demonstrated an ability to implement solutions and combine resources strategically, yet often prioritised short-term rewards over efficiency. The thematic vignettes illuminate these patterns where some players confidently applied management strategies, while others expressed frustration when faced with basic factual recall or analytical challenges (e.g. treasure box activating spread processes). Taken altogether, while players readily applied and evaluated knowledge within the game, obstacles remain (e.g. basic facts remembering and engaging with tasks requiring analytical reasoning), clearly demonstrating that cognitive process facilitation varies where manifestation depends on the information and game complexity presented.

5.3 Cognitive Dimension Modelling

5.3.1 Cognitive Process Facilitation

Advancing to the second aim of the study, the effects of game elements in KA were analysed through PLS-SEM. Path coefficient score between models reveals only a handful of hypothesised effects are reflected to be statistically significant (Figure 23). Among the exogenous constructs, in-game management shows a very strong and significant relationship with analysing, and strong statistical association with applying and evaluating (Table 6). Game events provide similar strong evidence association with analysing. Meanwhile, trivia demonstrates a strong link with applying. Meanwhile, quiz fails to reach statistical significance to any of the cognitive processes. In-game management among all the exogenous constructs was found to have *a very* strong link (Figure 23, red arrow) leading to analysing while the rest of the game elements, albeit statistically significant, showed only strong linkage.

Moving forward with cognitive processes, analysing shows a very strong association with spread mechanism and emerged as the strongest effect among all pathways according to path coefficient analysis. Applying significantly validates the expected directional effect with management practices, also exhibiting strong linkage similar to remembering leading to the learning content general information. Meanwhile, evaluating points out a meaningful strong connection to management practices; a path significance similarly demonstrated by understanding general information about *Pc*.

The results of path coefficient analysis briefly answer the first research question of the study, demonstrating the strength of each game elements in facilitating specific cognitive process. To simplify the empirical data, players acquired knowledge about spread mechanisms and management practices by the way they apply, analyse and evaluate game situations. However, the acquisition of knowledge gained concerning spread mechanisms is strongly linked with the players capacity to analyse the situation. In-game management serves as a strong element to harness such analytical thinking. Meanwhile, the learnings about the different management solutions are handled more by the respondent's ability to apply knowledge, through which trivia and in-game management has shown strong contributions. The concentration of very strong and strong path coefficient among constructs gravitating towards the middle- (applying) and higher-order (analysing, evaluating) thinking skills provide the backdrop that Silent Spread mainly caters knowledge application instead of merely knowledge absorption (remembering, understanding). Figure 23 visually summarises the observations raised.

5.3.2 Mediation Effects

Given the focus of the research to evaluate which game elements actually enhance learning, mediation effects among statistically significant pathways were further analysed. Specific indirect effects are preferred over total indirect effects because they allow the breaking down of each individual mediation pathway, thereby, improving precision and enables to answer the question which mediator (cognitive thinking process) matters in teaching particularly learning content.

Results reveal that the strongest pathway was found between in-game management and spread mechanism mediated by the thinking process analysing (Figure 24) (Table 9). Similarly, game events moderately contributed in indirectly teaching spread mechanism processes through the same thinking skill. Trivia influences imparting knowledge about management practices when applying was facilitated in the pathway while in-game management fosters the same learning content in congruence with both applying and evaluating, albeit demonstrated as only small indirect effects. Similar to earlier conclusion about quizzes, the game element demonstrated a weaker mediation effect, for instance, revealing negative and non-significant pathway leading to management practices through the cognitive processes.

In simpler terms and in congruence with the path coefficient analysis, specific indirect effects demonstrate that in-game management overpowers other game element, marking as the most powerful learning pathway, particularly in teaching spread mechanisms. In order to learn the different transmission processes, in-game management triggers players to analyse situations. Meanwhile, through the same game element, players had to apply their knowledge about the solutions so the management practice-related knowledge can be imparted within them. Game events also work the same way but to acquire disease spread knowledge, gamers are also encouraged to analyse situations. Trivia assisted mainly in imparting management practices but only when players are able to apply the foundational knowledge they obtained. Figure 24 illustrates the strength of various specific indirect effects of the four game elements.

5.3.3 Total effects

Building on the mediation analysis outcomes, the total effects provide a broader picture of how game elements as exogenous constructs and the final endogenous constructs are crudely linked (Figure 25). Consistent with earlier findings, in-game management still emerged to have the strongest positive effects exerting to spread mechanisms knowledge absorption (Table 10). Meanwhile, in-game management demonstrates moderate significant effects in facilitating the absorption of management practices through applying and evaluating. Game events, on the other hand, also revealed moderate contribution to assisting players in learning about spread mechanisms. Notably, trivia aids in reinforcing foundational knowledge about the general information of Pc; also demonstrating moderate total effects. It is worth-mentioning that the same element facilitates in management practice-related knowledge absorption, albeit, demonstrating smaller total effects as compared to the earlier two elements.

Notably, Figure 25 shows interesting visualisation about how trivia demonstrated a moderate significant total effect on generation information. The pathway highlights that while the direct path from trivia to general information was not statistically significant as shown in the path coefficient analysis (Figure 23), the accumulation of indirect contributions elevated trivia's overall influence to general information-related KA. In simpler words, trivia did not reinforce the learning content absorption as a single strong pathway, rather, accumulates the reinforcement through collectively strengthened cognitive processes (e.g. applying and understanding). For game events, the total effects shown that the element has moderate and significant total effects to management practices comprehension, however, this pathway did not reach statistical significance when path coefficient scores were examined (Figure 23).

To simplify the demonstration of total effect analysis, this step provides the overview of the game element efficacy, addressing the first research aim. In-game management consistently emerged as the stronger driver in imparting two learning outcomes, which are equally crucial in learning about the infestation spread processes and management of *Pc*. Game events follow as the second most effective. The element contributed moderately in facilitating the similar two pedagogical themes. Trivia, notably, plays a more supportive role to reinforce general information about the soil-borne pathogen and smaller effects in absorbing management practices-related knowledge, particularly when the cognitive process applying mediates the pathway.

Moderation effect analysis is originally considered in the study. As previously mentioned, there was a lack of meaningful variation across groups despite the richness of the socio-demographic profile. Given this situation, moderation effects were not further examined in this research.

Synthesising altogether the path coefficient scores, specific indirect effects and total effects, results consistently demonstrate that analysing is the most powerful thinking requirement to learn pathogen spread while in-game management is the core engine, consistently exhibiting strong outcomes across analysing, spread mechanism, evaluating, and management practices. This suggests that in-game management emerges as the most impactful game element in the game while trivia and game events contribute moderately. The effects of the latter two game elements are slightly lower than in-game management. Ultimately, while the game supports middle cognitive processes (applying), majority of the strongest outcomes lies on higher-order category (analysing, evaluating).

5.3.4 Assessment of R^2 and Effect Sizes

To further verify the earlier insights, the R^2 recommended values were adopted (Hair et al., 2021). Results verify that all the three endogenous constructs are substantially explained; all exhibiting substantial strength of model fit (Table 7) (Figure 23; See blue boxes). Furthermore, analysing and applying, albeit much lower than the endogenous constructs, still demonstrate substantial explanatory power. The remaining mediators exhibit moderate explanatory contribution. It is worth-mentioning that despite general information and management practices reached 1.00 R^2 unadjusted, upon verifying the HTMT (Heterotrait-Monotrait ratio), all constructs fall below the acceptable threshold (HTMT < 0.85). This careful inspection indicates good discriminant validity and distinctness of constructs. Interestingly, result further confirms that higher-order skills like applying, analysing, and evaluating are strongly explained, demonstrating that Silent Spread facilitated not just knowledge acquisition but a strong focus of fostering knowledge application.

Lastly, the analysis of effect sizes provides further insight into the magnitude of relationships within the model. In the lower order thinking processes, remembering and understanding extrude very large effects on general information while in-game management demonstrated strongest effects in congruence with analysing, applying and evaluating (Table 8). This shows that in-game management alone fosters this middle to higher-order processes. Game events, on the other hand, show notable medium effects on analysing and evaluating while analysing placed a critical role in advancing higher thinking domains, with a very large effect on spread mechanisms. These findings position analysing as major drivers among all higher-order skills while foundational thinking such as remembering and understanding contributes strongly in learning the pedagogical outcomes. Meanwhile, trivia also categorises as having small effects with evaluating and remembering yet exhibited moderate effects with applying.

Taken altogether, Silent Spreaffour d both support lower and higher-order cognition where analysing emerged as the central thinking process to learn pathogen transmission while in-game management consistently remain impactful across the tests.

5.3.5 Addressing model fit, sample size and other data limitations

Before ruling out the significance of constructs in facilitating KA and learning content, the study acknowledges that the structural model falls short to the overall fit model index following the Standardized Root Mean Square Residual (SRMR) threshold (Sarstedt et al., 2019; Hair et al., 2022). The results of Consistent PLS-SEM algorithm show that the model's SRMR scores (1^{st} model at 0.118) are higher than the conventional ≤ 0.08 benchmark. Despite these shortcomings, the results obtained are not completely invalidated. PLS-SEM is primarily based on variance prediction rather than covariance, entailing that the focus should rely on the significance and strength of relationships, rather than achieving the model fit. The study demonstrates such substantial values for exogenous and endogenous constructs with consistent significant paths; thus, the data presented still contributes to the understanding of game elements as knowledge facilitators.

It is also worth-noting to address the limitations of the small sample size (n=35). PLS-SEM holds the so-called "10x rule" wherein the participant size should be at least ten times larger than either the maximum number of formative indicators that shape the construct or the maximum number of structural paths leading into any endogenous latent variable. The two rules to be applied depend on the larger number that needs yielding. In this study, Management Practices denote the most demanding formative block ($N \geq 6 \times 10 = 60$). Meanwhile, the most heavily predicted endogenous construct requires four incoming paths, signifying $N \geq 4 \times 10 = 40$. The small sample size falls short of the conservative thresholds, the study presents high measurement and substantial effect sizes, enabling the sample size meets the minimum requirements of PLS-SEM under realistic yet well-acknowledged conditions. Hence, this research treats the overall results as exploratory and acknowledges the limitation the output suffered from.

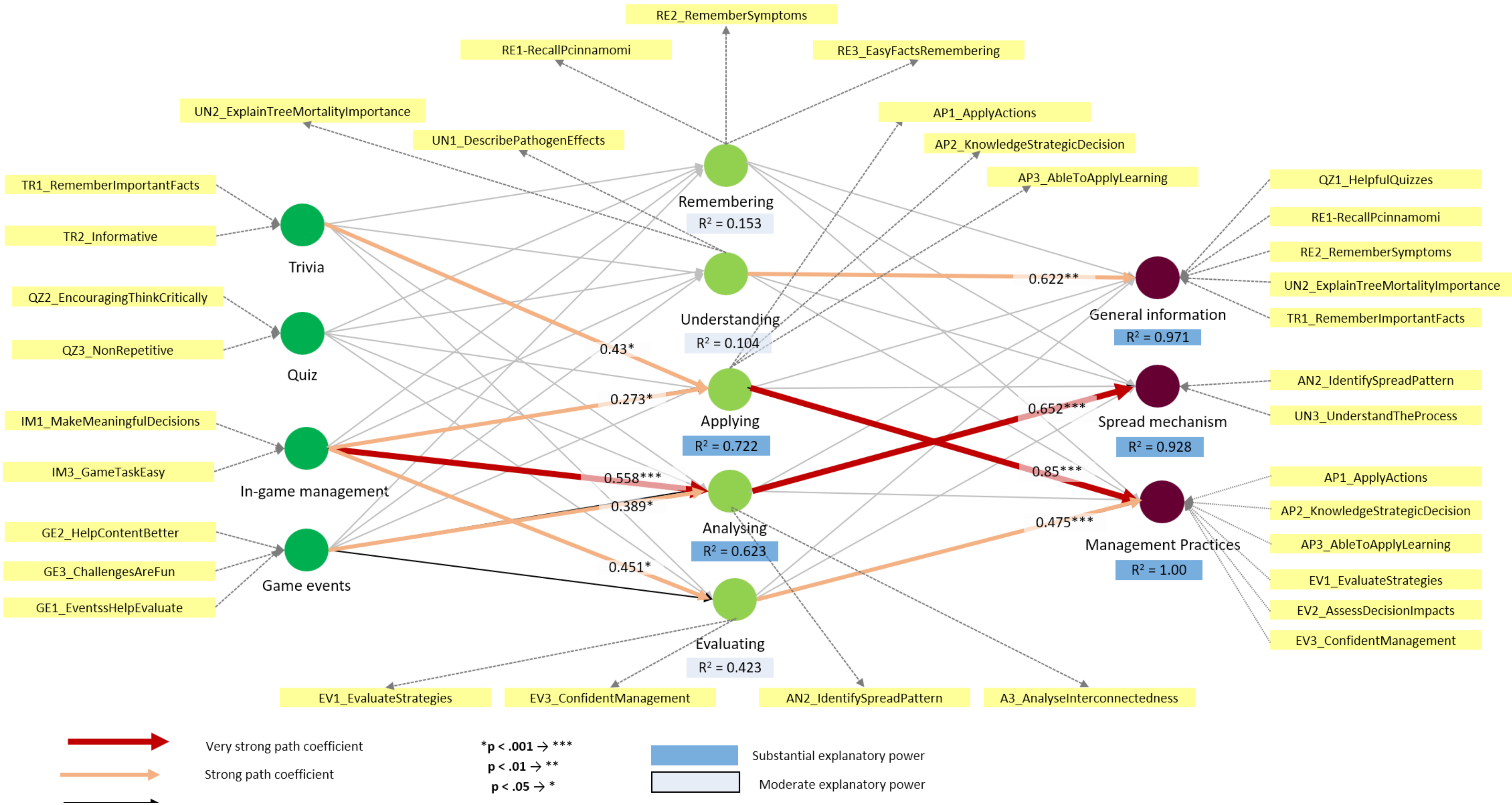


Figure 23. PLS-SEM results reveal the strength of pathways that reached statistical significance (red versus pink). Asterisks indicate levels of statistical significance: $p < .05$ (*), $p < .01$ (**), $p < .001$ (***). The model fit scored at 0.118 which is above the SRMR threshold 0.08 and was addressed in the results and discussion section of the study.

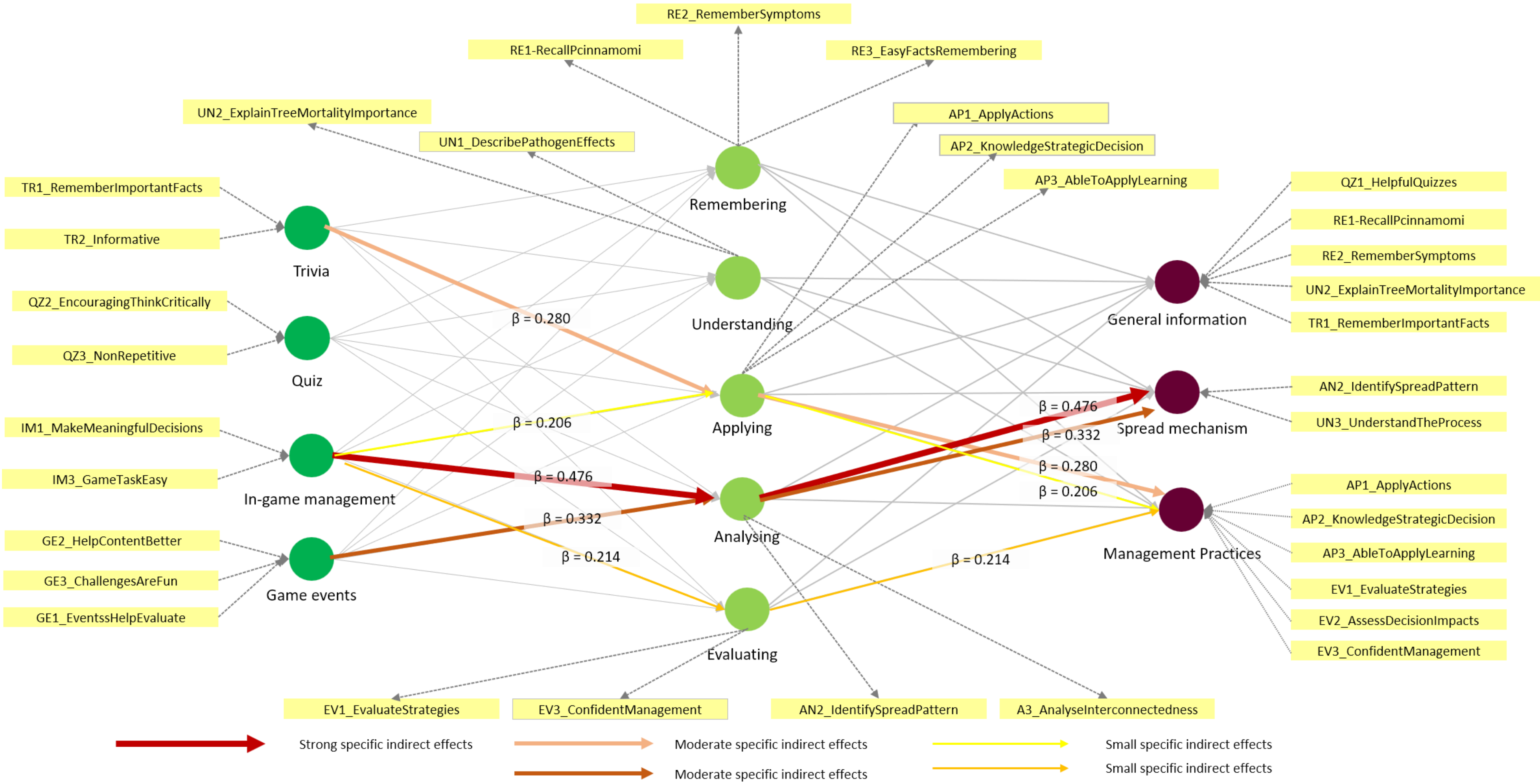


Figure 24 visually illustrates the results of specific indirect effects to establish mediation effects. Following the recommendations of Hair et al., (2017), the indirect effect values utilised in the interpretation are as follows: <0.10 as negligible, 0.10-0.20 for small indirect effect and 0.20-0.50 and 0.50 and above for moderate and strong specific indirect effects, respectively.

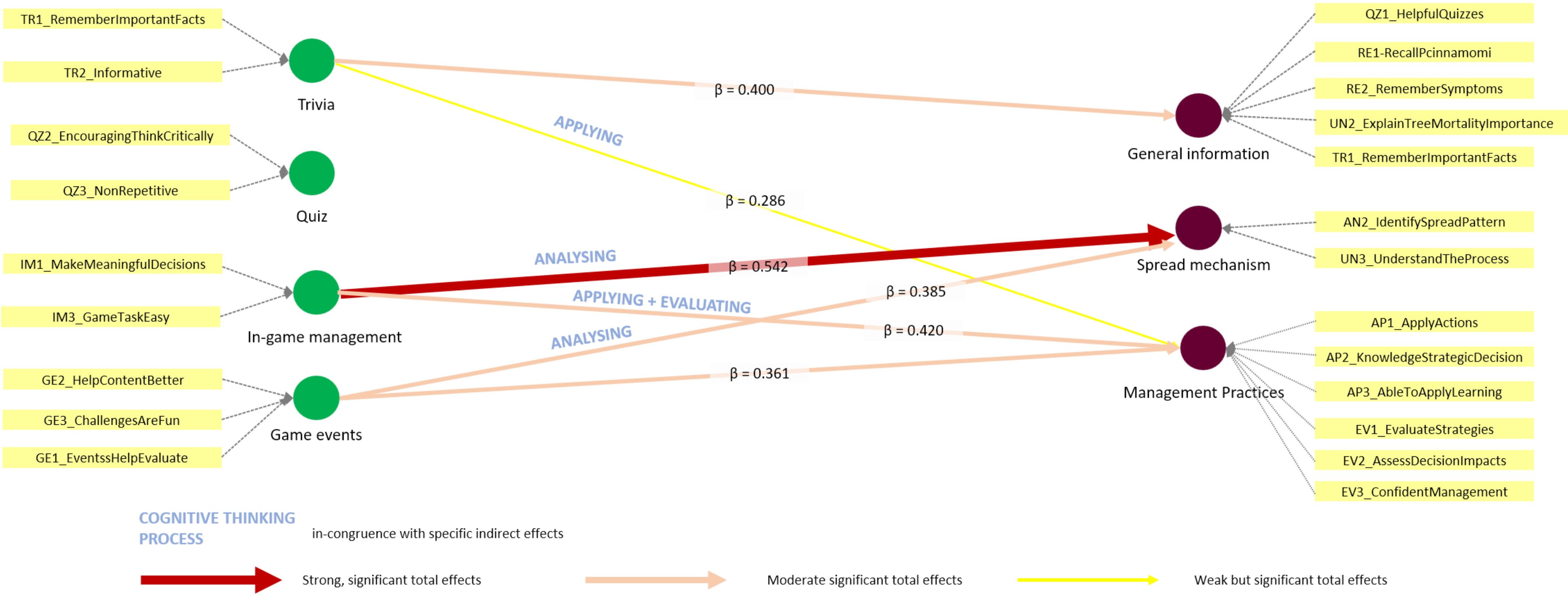


Figure 25 demonstrates the results of analysing total effects. The threshold follows the universal cut-offs (Hair et. al., 2017), wherein β ≥ 0.50 is considered to have strong total effects, and β ≈ 0.30 – 0.49 and β ≈ 0.10 – 0.29 for moderate and small effect, respectively.

Table 6. Summary of Path Coefficient, T-Statistics, and P-Value

Path	Original sample (O)	Sample mean (M)	STDEV	T statistics	P values
Remembering -> Management	0.000	0.000	0.000	0.000	1.000
Understanding -> Management	0.000	0.000	0.000	0.000	1.000
Analysing -> Management practices	-0.000	0.000	0.000	0.001	1.000
Game Events -> Remembering	-0.002	-0.009	0.319	0.005	0.996
Evaluating -> General information	0.003	-0.015	0.075	0.036	0.971
Trivia -> Evaluating	0.012	0.052	0.232	0.053	0.958
Analysing -> General information	-0.006	-0.031	0.092	0.063	0.950
Quiz -> Remembering	0.040	0.018	0.243	0.164	0.870
In-game management -> Understanding	0.067	0.098	0.275	0.244	0.807
Quiz -> Analysing	0.053	0.113	0.160	0.332	0.740
Game Events -> Understanding	0.116	0.094	0.292	0.399	0.690
Applying -> General information	0.053	0.074	0.105	0.508	0.611
Evaluating -> Spread Mechanism	0.046	0.043	0.081	0.567	0.571
Quiz -> Applying	0.073	0.102	0.121	0.601	0.548
In-game management -> Remembering	-0.152	-0.097	0.243	0.627	0.530
Remembering -> Spread Mechanism	-0.043	-0.030	0.065	0.666	0.506
Understanding -> Spread Mechanism	0.069	0.079	0.080	0.867	0.386
Applying -> Spread Mechanism	0.108	0.088	0.102	1.059	0.290
Trivia -> Understanding	0.247	0.274	0.222	1.114	0.265
Trivia -> Analysing	-0.199	-0.190	0.170	1.167	0.243
Quiz -> Understanding	-0.251	-0.242	0.206	1.220	0.222
Game Events -> Applying	0.227	0.237	0.158	1.438	0.150
Trivia -> Remembering	0.431	0.441	0.282	1.528	0.127
Quiz -> Evaluating	-0.337	-0.266	0.203	1.663	0.096
Game Events -> Evaluating	0.448	0.406	0.269	1.664	0.096
In-game management -> Evaluating	0.451	0.403	0.219	2.061	**0.039**
In-game management -> Applying	0.316	0.273	0.152	2.087	**0.037**
Game Events -> Analysing	0.389	0.373	0.174	2.236	**0.025**
Trivia -> Applying	0.430	0.428	0.145	2.959	**0.003**

In-game management -> Analysing	0.558	0.513	0.156	3.582	**0.000**
Understanding -> General information	0.438	0.451	0.111	3.934	**0.000**
Remembering -> General information	0.622	0.623	0.113	5.526	**0.000**
Evaluating -> Management practices	0.475	0.473	0.066	7.152	**0.000**
Analysing -> Spread Mechanism	0.852	0.850	0.096	8.868	**0.000**
Applying -> Management practices	0.651	0.655	0.047	13.919	**0.000**

Table 7. Summary of R^2 values

Path	R-square	R-square adjusted
Analysing	0.623	0.576
Applying	0.722	0.687
Evaluating	0.423	0.350
General information	0.971	0.967
Management practices	1.000	1.000
Remembering	0.153	0.047
Spread Mechanism	0.928	0.916
Understanding	0.104	-0.008

Table 8. Summary of Effect Sizes

	Analysing	Applying	Evaluating	Game Events	General information	In-game management	Management practices	Quiz	Remembering	Spread Mechanism	Trivia	Understanding
Remembering					**7.034**		∞			0.013		
Understanding					**2.803**		n/a			0.028		
Applying					0.053		∞			0.086		
Analysing					0.001		n/a			4.438		
Evaluating					0.000		∞			0.011		
Game Events	**0.222**	0.103	**0.192**							0.000		0.008
General information												
In-game management	**0.418**	**0.182**	**0.178**							0.014		0.003

Management practices												
Quiz	0.004	0.011	0.117							0.001		0.042
Spread Mechanism												
Trivia	0.072	0.455	0.000						0.150		0.047	

Table 9. Summary of Specific Indirect Effects

Path	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
In game management -> Analysing -> Spread Mechanism	0.476	0.434	0.136	3.508	0.000
Trivia -> Applying -> Management practices	0.280	0.280	0.095	2.947	0.003
Game Events -> Analysing -> Spread Mechanism	0.332	0.315	0.148	2.244	0.025
In game management -> Applying -> Management practices	0.224	0.181	0.104	1.972	0.049
In game management -> Evaluating -> Management practices	0.210	0.192	0.099	1.965	0.049
Quiz -> Evaluating -> Management practices	-0.160	-0.123	0.095	1.684	0.092
Game Events -> Evaluating -> Management practices	0.210	0.191	0.130	1.631	0.103
Trivia -> Remembering -> General information	0.268	0.270	0.186	1.441	0.150
Game Events -> Applying -> Management practices	0.148	0.154	0.105	1.417	0.156
Trivia -> Analysing -> Spread Mechanism	-0.169	-0.165	0.149	1.133	0.257
Quiz -> Understanding -> General information	-0.110	-0.109	0.098	1.123	0.261
In game management -> Spread Mechanism	0.034	0.022	0.033	1.030	0.303
Trivia -> Understanding -> General information	0.108	0.129	0.111	0.977	0.328
Trivia -> Applying -> Spread Mechanism	0.046	0.040	0.049	0.954	0.340
Game Events -> Applying -> Spread Mechanism	0.024	0.022	0.031	0.781	0.435
Quiz -> Understanding -> Spread Mechanism	0.017	0.016	0.028	0.629	0.529
In game management -> Remembering -> General information	-0.095	-0.066	0.158	0.599	0.549
Quiz -> Applying -> Management practices	0.047	0.066	0.079	0.595	0.552

In game management -> Evaluating -> Spread Mechanism	0.021	0.014	0.036	0.569	0.569
Quiz -> Evaluating -> Spread Mechanism	0.015	0.021	0.028	0.556	0.578
Trivia -> Understanding -> Spread Mechanism	0.019	0.022	0.034	0.507	0.612
Trivia -> Remembering -> Spread Mechanism	-0.019	-0.012	0.038	0.495	0.620
Game Events -> Evaluating -> Spread Mechanism	0.023	0.023	0.042	0.494	0.621
Trivia -> Applying -> General information	0.023	0.030	0.048	0.478	0.633
Quiz -> Applying -> Spread Mechanism	0.020	0.021	0.030	0.450	0.667
Game Events -> Understanding -> General information	0.051	0.044	0.136	0.375	0.707
Trivia -> Applying -> General information	0.019	0.023	0.033	0.372	0.710
In game management -> Remembering -> Spread Mechanism	0.007	0.004	0.019	0.354	0.723
Quiz -> Analyzing -> Spread Mechanism	0.045	0.099	0.140	0.323	0.747
In game management -> Understanding -> Spread Mechanism	0.029	0.014	0.033	0.241	0.810
Quiz -> Applying -> General information	0.008	0.008	0.018	0.210	0.833
Quiz -> Remembering -> General information	0.025	0.014	0.154	0.161	0.872
Quiz -> Evaluating -> General information	0.005	0.004	0.031	0.152	0.880
Quiz -> Remembering -> Spread Mechanism	-0.002	-0.001	0.017	0.099	0.921
Quiz -> Remembering -> Spread Mechanism	-0.002	-0.001	0.017	0.099	0.921
In game management -> Analyzing -> General information	-0.002	-0.016	0.051	0.063	0.950
Game Events -> Analyzing -> General information	-0.002	-0.013	0.041	0.055	0.956
Trivia -> Analyzing -> Management practices	0.006	0.018	0.108	0.054	0.957
Quiz -> Evaluating -> General information	0.001	0.000	0.025	0.036	0.971
In game management -> Evaluating -> General information	0.001	-0.009	0.035	0.035	0.972
Game Events -> Evaluating -> General information	0.001	-0.006	0.032	0.032	0.974
Trivia -> Evaluating -> Spread Mechanism	0.001	0.005	0.024	0.024	0.981
Quiz -> Analyzing -> General information	0.001	0.000	0.018	0.018	0.986
Game Events -> Remembering -> General information	0.003	-0.003	0.202	0.023	0.990

Game Events -> Remembering -> Spread Mechanism	0.003	0.003	0.023	0.023	0.998
Trivia -> Evaluating -> General information	0.002	0.002	0.009	0.002	0.999
Quiz -> Understanding -> Management practices	-0.002	0.000	0.003	0.000	1.000
Game Events -> Remembering -> Management practices	0.002	0.000	0.002	0.000	1.000
In game management -> Remembering -> Management practices	0.000	0.000	0.000	0.000	1.000
Quiz -> Remembering -> Management practices	0.000	0.000	0.000	0.000	1.000
Game Events -> Analyzing -> Management practices	0.000	0.000	0.000	0.000	1.000

Table 10. Summary of Total Effects

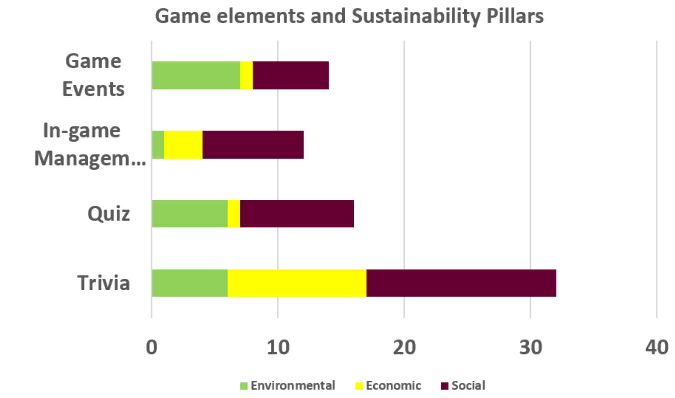
Path	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Analysing -> Spread Mechanism	0.852	0.850	0.096	8.868	**0.000**
Applying -> Management practices	0.651	0.655	0.047	13.919	**0.000**
Evaluating -> Management practices	0.475	0.473	0.066	7.152	**0.000**
In-game management -> Analysing	0.558	0.513	0.156	3.582	**0.000**
In-game management -> Spread Mechanism	0.542	0.477	0.147	3.674	**0.000**
Remembering -> General information	0.622	0.623	0.113	5.526	**0.000**
Understanding -> General information	0.438	0.451	0.111	3.934	**0.000**
Trivia -> Applying	0.430	0.428	0.145	2.959	**0.003**
In-game management -> Management practices	0.420	0.373	0.166	2.537	**0.011**
Game Events -> Analysing	0.389	0.373	0.174	2.236	**0.025**
Game Events -> Spread Mechanism	0.385	0.376	0.176	2.190	**0.029**
In-game management -> Applying	0.316	0.273	0.152	2.087	**0.037**
In-game management -> Evaluating	0.451	0.403	0.219	2.061	**0.039**
Game Events -> Management practices	0.361	0.345	0.195	1.846	0.065
Game Events -> Evaluating	0.448	0.406	0.269	1.664	0.096
Quiz -> Evaluating	-0.337	-0.266	0.203	1.663	0.096
Trivia -> General information	0.400	0.432	0.247	1.621	0.105

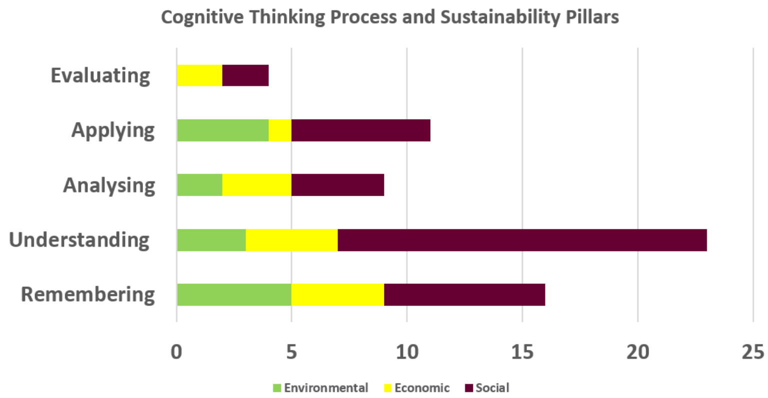
5.4 Post-Game Reflection

5.4.1 The Cognitive Sustainability Compass

The compass aims to capture the highest thinking skill in the BCD framework, *creating*. Results of the frequency count reveal that trivia emerges as the most recurrently cited game element, particularly under the social and economic sustainability pillars (Figure 26). Quiz was used half as often as trivia but closely followed by game events and in-game management. Despite in-game management ranking last, data indicates that there was proximity in terms of frequency usage among the three game elements. Results also reveal that lower-order thinking skills such as remembering and understanding received the greatest number of matches during cognitive mapping, respectively. Interestingly, the sudden surge of increase (n-16) in matching understanding as the thinking process happened during social sustainability concept association; a finding that was not observed on any of the other cognitive processes. Applying and analysing had marginal differences while evaluating ranked the least.

Majority of the sustainability reflections fall under social components followed by environment-related responses, leaving economic sustainability least explored. Concepts such as the role of digital technologies in learning about the pathogen spread, digital games as investment in education and collaborative problem-solving were some of the most extensively cited social dimensions during the card-sorting activity. For instance, one participant reiterated, "In Level 1 and 2 we are competitors but in Level 3, we reach to a point that we are losing the game and realised that collaboration is important." Moreover, participants noted their reflection on the understanding of spatial-based pest disease dispersion, the biophysical factors that facilitate transmission, and agrifood system when asked about environmental sustainability pillars. Lastly, concepts tangled with economic sustainability pillars centre on the impacts of tree mortality to acorn production, and the cost-benefit analysis of





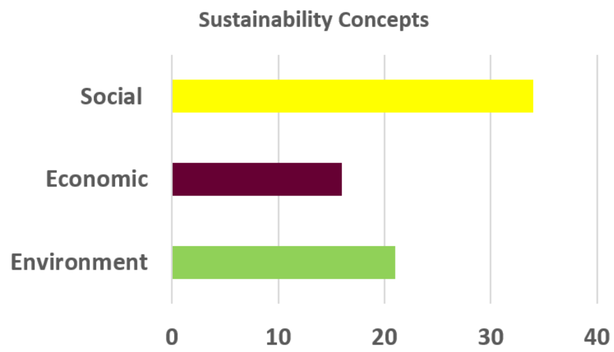


Figure 26 summarises the frequency through which each game elements, and cognitive thinking processes are used during the card-sorting activity. The bottom left panel shows the number of sustainability concepts reiterated by the players, which heavily concentrates on social sustainability pillar.

managing the infestation. Several participants also reflected on the roles of agrifood system as a source of income and short term versus long term gains in managing the infestation under the economic discussion.

5.4.2 Thematic Vignette Post-Cognitive Sustainability Compass Session

Beyond the most frequently cited sustainability reflections, several noteworthy themes emerged during the activity. For many players, the game facilitated collaborative problem-solving, allowing them to reflect on the need for multi-stakeholder engagement in battling the infestation. In-game management and game events, given their analytical requirement, activated the cooperation among players to fight the spread that despite the game designed to facilitate competition, one participant mentioned that they ended up being teammates in Level 3. Such dynamics mirrors real-life scenarios where solving the infestation problem requires multiple actors. The game also served as a means to connect the respondents to rural issues. One participant remarked, "I feel more connected with social rural issues, you get to understand the plight of farmers and how they deal with such challenges they go through. You as a practitioner, you connect yourself with their challenges." Participants also made illustrative example about in-game management challenges activated their analytical skill to find the best solution, later making them feel more connected with real issues and challenges such as the biodiversity threat in the area. According to participants, by grasping the real problems farms face, their perception and attitude also change, making them realise the part they share in problem-solving. However, at least two of the players mentioned that there should have holistic view in addressing the pathogen infestation because at the end of the day, it is the farmers who will tackle the issue on the ground. Beyond personal connection to rural issues, sustainable production education was also a key theme during the reflections. One student reiterated how interacting with SGs can increase public awareness due to the game's engagement-inducing effect and proposed that digital games require investment for education and theory-sharing. Sustainable production was also associated with how Iberian pigs and acorn are intertwined, proving that knowledge acquisition such as analytical trade-off thinking took part during the in-game sessions.

On the one hand, conceptualisation such as learning the technical foundations of fighting *Pc* and the solutions to halt biodiversity loss emerged as key themes under environmental sustainability pillar. Participants praised how the game ignited their interests in Pc, particularly in equipping them with technical management solutions. One participant noted that measures can be as simple as erecting fence to help prevent the spread but solutions like the use of Trichoderma spp. against *Pc* brings the idea of "fighting nature with nature". Moreover, quiz acted as a reminder to pay close attention to trivia which solidified their understanding about IPM, supporting that Silent Spread was successful in teaching different management practices and associating their own knowledge about pest infestation. For instance, one player shared that similar in a sugar cane in the US, when one plant gets infected, farmers would be taking down an entire row of plants, proving that the game surpassed lower thinking skills facilitation but moved beyond applying and analysing related scenarios. Understanding spread mechanisms were also mentioned several times. One student even narrated the entire pathogen spread narratives, from identifying problems, learning about management solutions, to controlling further disease dispersion. Such post-game reflections echo the cognitive facilitation impacts of digital SGs.

Players identified the game's capabilities to teach production economics. Recurring discussions include how they learned about the trade-offs between tree mortality rate and acorn production, and its impacts to Iberian pig economy. One player mentioned that trivia brought some insights on how important it is to control the pathogen and reduce further economic losses. A participant mentioned, "We have a baseline understanding of agrifood-system based economy, not just the income but also the acorn production. They [farmers] provide acorns that would be fed to Iberian pigs which would give us more economic benefits in combination with benefits to the ecosystem. So, trivia, events and in-game management, we realise the importance of healthy ecosystem for rural livelihood." Respondents also navigated situations wherein assessing the entire infestation problem entails learning about the different management practices that best suit the situation. This analytical reflection, in turn, allowed them to understand the cost-benefit interchange in pathogen management. In support to this, another player emphasised that game events enable the ability to understand and apply solutions which in a way would help them remember the importance of healthy ecosystem for rural livelihood.

Overall, the Cognitive Sustainability Compass-making session illustrates that participants were able to associate in-game learnings to sustainability concepts. The result of the activity demonstrates that players captured the higher thinking level, 'creating'. Key recurring reflections emphasise the complexity, interrelatedness, and cause-and-effect dimensions of pathogen management. Additionally, the respondents reiterated that despite some concepts being placed in one aspect of the compass, many of the reflections overlap with one another, showing either causal or spillover effect relationships. Moreover, game elements exceeded the intentional pedagogical contributions as many players withdraw from a single information and skill source to multiple elements working alongside to facilitate cognitive skill development.

Table 11: Thematic Sustainability Pillar and Quote Matrix

Environmental Sustainability Pillars			
Theme	**Game Element**	**Cognitive Process**	**Chosen Quote**
Learning about the pathogen	All game elements	Remembering, Understanding, Applying	I think each element is important for me to understand what the game is about and how it could help the pathogen problem. I cannot separate each element in order for me to understand, apply, and remember. It [the game] helped me understand that if you use this kind of technology, there is another way to help the farmers. I am quite confused how we are going to translate this to farmers who are eventually the ones who would be there on the ground fighting the disease, from production to technical solutions.
Understanding disease spread	Quiz	Analysing	Just learning about the spread of it [the pathogen], how easy it is to spread like the shoe washing station. Where we are in States, they would be cutting sugar cane and when one of them is infected, they would be taking down the rest of them.
IPM	Trivia, Quiz	Understanding, Remembering, Evaluating Remembering	You get to understand first how the pathogen spreads and then we get to know how to manage it, how to control the dispersion. First, you identify what and where the transmission and based on that you know which one can be avoided, which one can be controlled, which one can be treated and that is very important.

	In-game management		In-game management helped me remember the importance of integrated pest management. I learned about root barriers which I think is very important in this regard where it helps me understand the different management practices that could be useful. With resilience, some of the measures is simple like erecting fence and that would be enough to help prevent a spread, that was kind of shocking. That one species that act as parasitic to the fungi. It was cool to fight nature by nature instead of chemicals.
Biodiversity Conservation	Trivia; In-game management	Analysing; Applying	Because through the combination of trivia, you understand biodiversity loss, you understand something about it and then you have the in-game management. So, from that you will understand biodiversity loss. You apply possible solutions for biodiversity loss. There is an intersection, a nexus for biodiversity loss to be under environmental, social, and economic pillar.
Social Sustainability Pillars			
Collaborative problem solving	Quiz	Applying	For me I put trust together with quizzes. Even if we are competitors, we are trying to help each other understand the problem and then apply solutions to it as well.
	Event	Understanding	For me the event helps me understand and more connected to rural issues because we are doing collaborative problem solving.
Connection with rural realities	Quiz, Trivia	Understanding	I feel more connected with social rural issues, especially with somebody with my background, you get to understand the plight of farmers and how they deal with such challenges they go through. You as a practitioner, you connect yourself with their challenges.
	Quiz	Analysing	The quiz gives options in the quizzes helping you analyse which solution fits best. So, you feel more connected with the real issues and challenges. At the end of session, you realise it [the issue], that affects one part but the entire community as well, especially biodiversity in the area.
Education and knowledge sharing	Game event	Evaluating	For the game event, you were able to evaluate sustainable production education, which means that you understand the social and economic dimensions. For example, in acorn production you decide how many pigs do you have but at the same time you foster education and knowledge to make the system more sustainable.

			If you interact with this kind of technology, you will be able to increase public awareness because serious games make it more engaging for people, but I don't know for farmers. I think we need to have holistic view and cannot separate. I think we can spend money for digital games to spread education and theory.
Changing attitudes and perceptions	Trivia, Quiz, In-game management	Evaluating	Trivia, in-game management and quizzes help you change your perception in terms of grasping the real problem in your farm, for example in understanding biodiversity and through that you would be able to change as well, that now your perception has been change that you have a part in solving the loss of biodiversity. You have your own share of solving the problem.
Multi-stakeholder engagement	All game elements	Evaluating	There is a need for multi-stakeholder cooperation because in the game you are able to see that one player cannot do everything. You need at least another person to help you, hence, the need for multiple collaboration to solve the entire thing.
	In-game management	Understanding, Analysing	I really like in the game is the in-game management, especially in level 3. Because in Level 1 and 2, we are more of considering ourselves as competitors but in level 3, we reach to a point where we are losing the game by playing separately. So, I understand that if I combine strategies, I would like to emphasize the collaborative problem solving instead of being competitors, we ended up being teammates.
Economic Sustainability Pillar			
Balancing costs with management benefits	Trivia	Evaluating, Analysing	Some of the trivia, you could see how farms suffer from economic losses and that brought some insights how important it is to control this kind of pathogen.
	Quiz	Understanding, Analysing	I have an understanding of cost and benefit in managing the infestation like we have a lot of management practices that are applicable in situations, so we need to assess the entire picture before we employ one or more practices to control the situation.
Sustaining production and income, and rural livelihood	Trivia	Remembering	I was thinking that if there is a lesson from the game, it is the fact that you have to reduce the herd size in terms of tree mortality, thereby, affecting your production as well. If you are economically minded, you want to prevent the spread as much as possible.

	All game elements	Understanding, Evaluating	My understanding of the ecosystem is based on trivia where we all started. So, we have a baseline understanding of agrifood-system based income, not just the income but also the acorn production. They [farmers] provide acorns that would be fed to Iberian pigs which would give us more economic benefits in combination with benefits to the ecosystem. So, trivia, events and in-game management, we realise the importance of helathy ecosystem for rural livelihood. There is no separation of environment and economic, we emphasise the importance of collaborative problem-solving. The people are managing the ecosystems but we are just one part of a bigger whole, this is not just a collaboration for people to people but people to nature.
	Game event	Understanding, Applying	In the game event, you have the ability to understand and apply integrated pest management. In a way, you would remember the importance of healthy ecosystem for rural livelihood. Everything follows. If you have a healthy ecosystem, you have a vibrant rural livelihood.

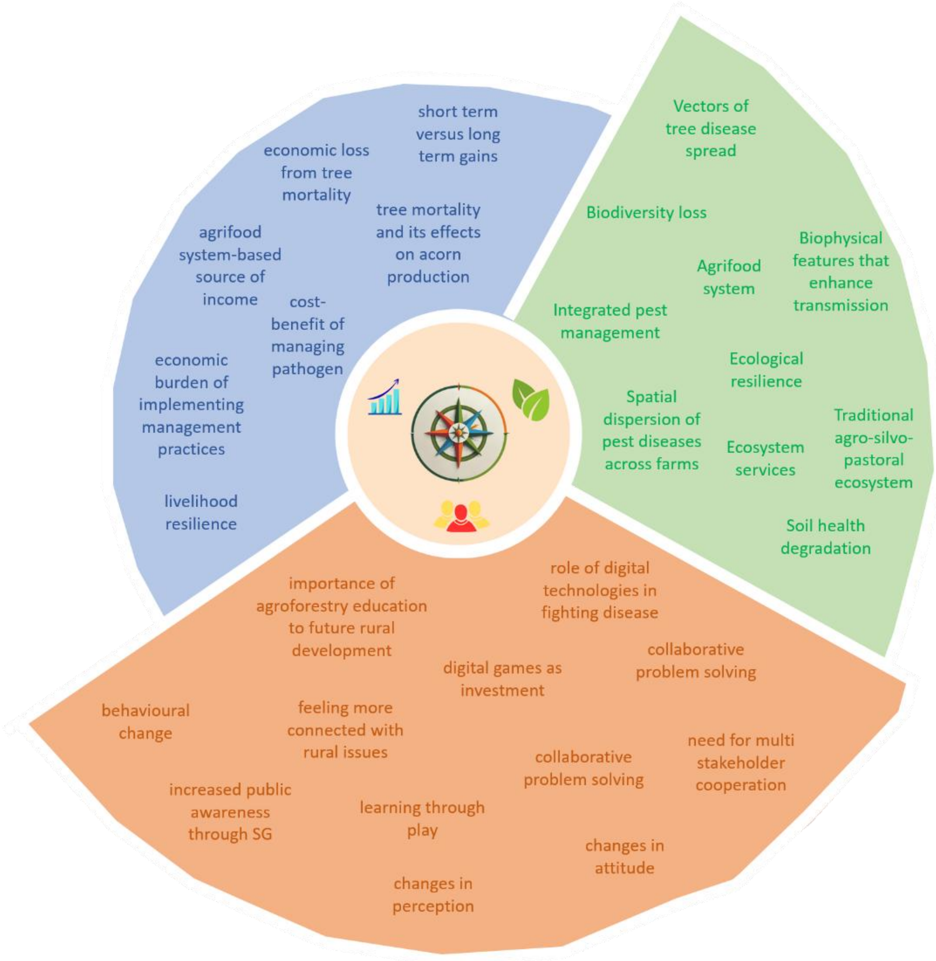


Figure 27. A visualisation of the Cognitive Sustainability Compass output consolidating all the reflections froom the 17 participants.

Figure 28. Some of the examples Cognitive Sustainability Compass created by the 17 participants who agreed to do the post-game reflection activity.

5.4.3 Participant Reflection on Game Elements

The last section of the results of the study summarises the participants positive and negative reflections on each game elements. Firstly, learners emphasised that the addition of audio support combined with digestible texts highly aided the factual information from trivia. Players remarked that they no longer need to read the texts, reducing the tendencies to skip the trivia. One participant even noted that human voice instead of AI-generated audio would have been more engaging. Text typologies such as underlined and bold words underscore important facts that later aided in answering the quizzes. However, there is ambivalence about the technical content and how participants perceived them. Others noted that the scientific words fortify the key knowledge about Pc while some demanded to make the content more accessible to the general public, particularly those without background in invasion biology. Players also noted that the mechanics to emphasise scientific words, technical content, literature references, and statistics are important part of the trivia and the game as a whole. Respondents also detail the confusing nature of numeric details, and some cards are lengthy and too advanced making it difficult for players to remember and digest the content.

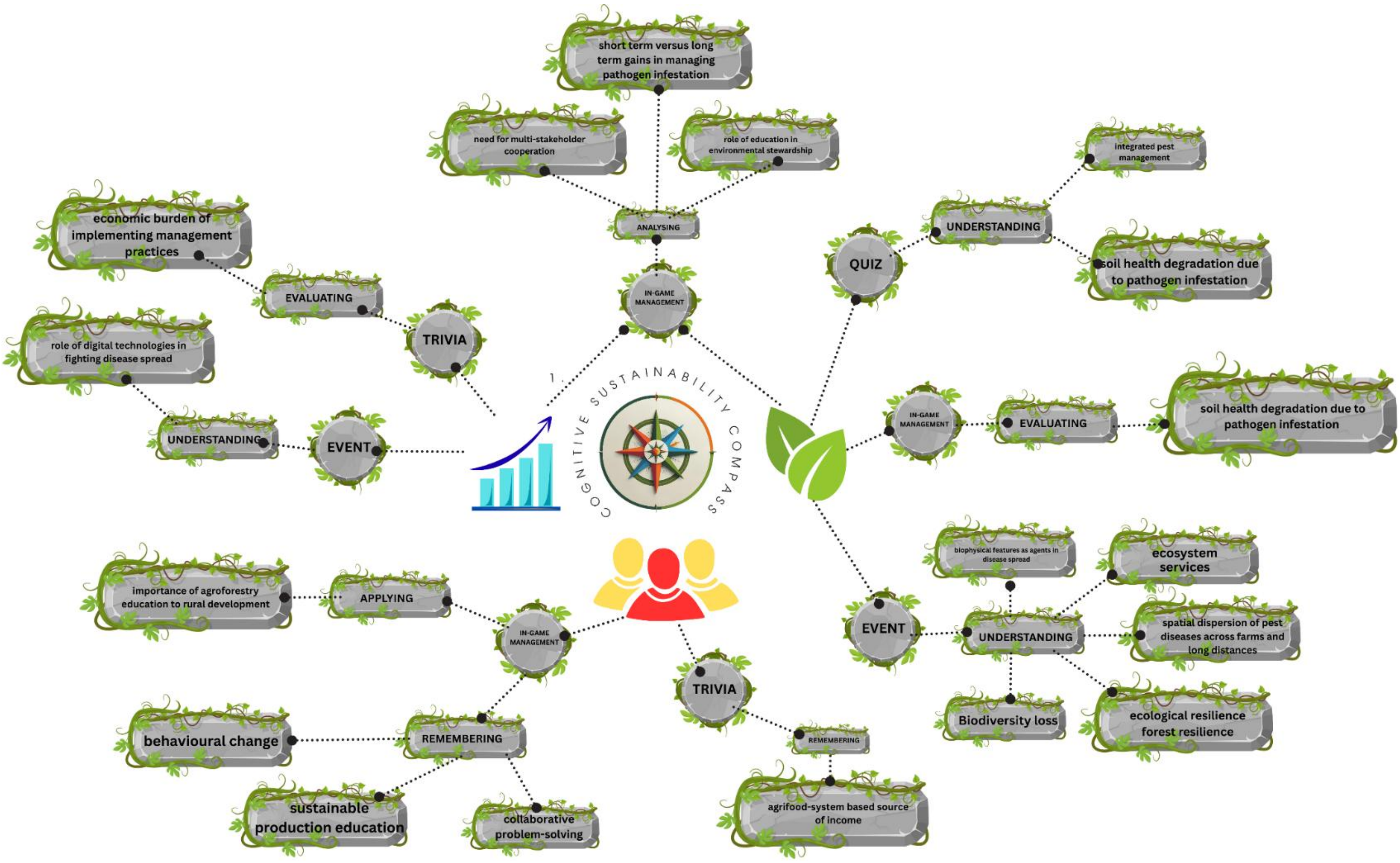


Figure 29. A digitised version of one of the Cognitive Sustainability Compass made by the group from SPU Nitra.

Quizzes, on the one hand, were praised for acting as a reminder of the information players have forgotten from trivia cards and an actual measurement of the in-game learnings, making the learning experience more fun and engaging. Game testers specifically mentioned that quizzes encouraged them to pay close attention to the learning content, prepare for the questions later in the game, and foster a sense of satisfaction due to the embedded reward system. The element also unravelled opportunities for players to discuss their own content understanding and raise analytical arguments with one another. Recommendations on improving the game element include an automatic checking of answers, limiting the options to few, and fixing the sequence through which quizzes appear once the supplementary materials have been explored. In general, quizzes acted as a measure of comprehension players retrieved from the trivia.

Players noted that in-game management expanded their knowledge about different solutions despite not having prior educational training about *Pc* infestation. Similarly, participants felt they gained control of the pathogen problem by applying the solutions to particular contexts, enabling autonomy in decision-making, and experiencing forest management in a digital and simulated environment. Notably, many participants advised to automate the efficacy of management practices, either in earning the respective rewards or signifying that the infestation has been prevented. Players also emphasised the lack of assessment whether the correct management solution was applied to the respective infestation context. Such quick in-game feedback combined with visual overload, particularly in level 3 later resulted to reduced engagement and frustration according to some game testers.

Lastly, there was mixed perceptions about game events and its interpretation to players. Some participants praised the minute details game events provide such as unclean boots, rainfall, and farm activities as major transmission vector, adding extra layer of information source. Others also added that events provided game complexity that activates strategy thinking by learning about various transmission scenarios and understanding real world problems. Despite positive feedback, reflections such as confusing, visually overwhelming, and frustrating were also pointed out post-game. Majority of the overwhelming reactions rooted from the treasure box where players first analyse the transmission process that have occurred, then tasked to answer which factor most likely facilitated the infestation.

5.4.4 Points for Improvement

Players also suggested several improvements that could make the game engaging, and technically effective. One common feedback was the need for smoother functionality, with participants mentioning the absence of a pause button and the occasional lag, later causing game flow interruption. Others remarked that automating some processes, such as the spread of footsteps, scoring, and the allocation of rewards, would lessen errors and reduce unnecessary repetition. One player remarked that automated debriefing would help players whether the management decision was appropriate for the spread scenario. The punish–reward system was also described as needing more clarity, as some players felt unsure about when and how they were rewarded or penalised. Similarly, the importance of turn-taking was highlighted to avoid random clicking and ensure fairer play across participants.

In terms of content, learners recommended refining the phrasing of questions and instructions so they were clearer and easier to follow. Some players wanted more introductory information on the pathogen to help them connect the gameplay with its ecological context, while others suggested simplifying the number of options in certain stages to avoid confusion. The visual design of the game was also a recurring theme in the suggestions. A few participants noted minimising the visual presentation would not only make the game more appealing but also prevent visual overload. Players observed that smoother transitions and clearer design choices could help them focus on the learning content rather than being distracted by layout and aesthetics.

Finally, the structure of multiplayer dynamics received attention. Some participants proposed limiting the number of players in a single session, suggesting that three might be the ideal number to keep discussions manageable and engaging. Others pointed out that more time should be allocated to each level to allow reflection before making decisions. These reflections indicate that while the game was successful in fostering learning, addressing functionality, clarity of content, design, and player dynamics would further strengthen both the educational and entertainment value of the experience.

6. Discussion

6.1 Academic value

The study contributed to the growing literature about SG as a tool in imparting agricultural knowledge and innovation system (Dernat et al., 2025, p. 2; Klerkx, 2020). Specifically, the results advance SG scholarship twofold. Firstly, the development of Silent Spread added to the limited empirical exploration of SG in IPM, addressing the identified methodological and empirical gaps of the study. Such contributions assist in the urgency to engage the broader public to learn and teach pest management (de la Vega et al., 2022), emphasising the role of communities in preventing future transmission. People in industrialised economies are disconnected in pest problems (Sutherland et al., 2020). The detachment further galvanises the potential impact of Silent Spread in agrifood system transformation in Spain and other countries.

The second contribution to the SG literature sheds light on game elements that can enhance respective thinking skills, in turn, tackling the lack of structured guidance in properly designing SG (Boyle, Connoly, & Hainery, 2011) and the absence of strong theory-grounded frameworks in developing learning systems (Khaldi et al., 2023). The current research addresses the hitherto operationalisation of BCD in IPM-contextualised SG, corresponding to the integrated theoretical application, methodological and empirical gap of the current research. Such methodological and theoretical anchoring positions BCD as both an evaluative tool for learning assessment and facilitative instrument to target specific thinking process. This aligns with the earlier studies of Ambawati & Ardi (2019) and Juan & Chao (2015) on lower-order thinking skills and Thomas (2002) who explored attitude and behavioural change as catalyst for higher cognitive processes. However, it is worth mentioning that the current study is unique in a sense that the thinking skills were assessed both in-game (i.e. PLS-SEM, in-game performance) and post-game reflections (i.e. Cognitive Sustainability Compass). The study argues that such coupled learning outcome assessments explore BCD's game manifestation as knowledge absorption (i.e. in-game performance) and knowledge application learning outcomes (i.e. post-game reflections). Crucially, the efficacy of gamified interventions (e.g. trivia, quiz, in-game management, game events) demand theoretical grounding (Krath et al., 2021). Through the combined support of PLS-SEM calculation and sustainability concept mapping activities post-game, the findings made clear that particular game components can laser target specific cognitive processes, a rather important puzzle piece in shaping the theoretical foundation game design currently lacks (Krath et al., 2021).

6.2 Key takeaways

Reorienting to the central research aim and questions, the study demonstrates that integrating BCD into SG successfully facilitated learner's KA on Pc's spread mechanisms and management practices. The knowledge implementation benefits are expected since the game was designed following the recommendations to match the narrative with the learning material (Bellotti, et al., 20212). Game narratives are exemplified in trivia about *Pc* the quick knowledge absorption assessment through quizzes, the context through which each in-game management solution can be applied to, and the game events which detail how tree disease transmission spread through human, and biophysical factors. Narratives are also considered as sensory stimuli which increases player engagement with the instructional material (Ke & Abras, 2013). The stimulating effect of narratives combined with the four game elements further explain how the two learning contents, spread mechanisms and management practices, shown statistical significance when pathway from certain game elements were evaluated.

Another key finding denotes that the efficacy of sharpening particular cognitive process can be evaluated through complementary tools (i.e. in-game performance, PLS-SEM, post-game reflection). With critical consciousness, the use of several assessment methods in the current study likely supports the fragmented (Connoly et al., 2012) and incoherent (Ke, 2009) collective agreement on the positive outcomes of games (Connoly et al., 2012). However, by demonstrating the vulnerability on the shift in knowledge facilitation underscore games capabilities to foster intended knowledge and skills (O'Neil et al., 2013) but clearly, caution on game design and type of SG to be used must be strictly observed. To reiterate, the research utilised three tools consistent with earlier literature such as the use in-game performance or analytics (e.g. Strada et al., 2023), and the mirroring of PLS-SEM calculation employed by Mohamed et al., (2023), and Lin (2020), while the use of Cognitive Sustainability Compass as post-game reflection tool is unique to the study. The variation on cognitive sharpening based on evaluation lens is expected since measured learning gains vary widely on the assessment method (Udeozor et al., 2024; Gris et al., 2021). This elevates the conversation that there should have in-game analytics assessment and post-gameplay reflections beyond the conventional pre- and post-test approaches in SG assessment. To illustrate this, both the quantitative and qualitative lenses are unpacked in the succeeding discussions.

6.2.1 In-game management as the strongest driver but game events and trivia support substantially, too

In a quantitative lens, path modelling illustrated that certain game elements exhibited stronger influencer than the others, further supporting the hypothesis of the study. The differential effects exhibited by game interventions is nothing new, which can be explained by two interaction strategies. Video games, in general, have two interaction strategies: an event-based strategy which triggers player action based on presented events, and state-based that dictate what players can do depending on the current system state (Drachen, et al., 2013). Trivia and game events fall under the event-based category, in-game management starts from event-based which transitions to state-based, while quizzes can be considered as a hybrid. Conversely, the manner through which players engage with particular game elements affects the degree of interaction between players (Teichmann, et al., 2020), produce different mindful decisions (Wong et al., 2024) and actions (Altomari et al, 2023). As an effect, players will be sharpening specific thinking process as observed in the study (Figure 23). This further exemplifies that different game elements exhibit efficacy in promoting different engagement, hence, enhancing different learning processes (Abdul Jabbar & Felicia, 2015).

Notably, the path modelling also demonstrated that not all cognitive processes are fostered by the game elements. In fact, only the middle to higher-order thinking skills is fully captured, leaving the lower-order cognitive processes statistically insignificant. Such findings fail to capture the hypothesis stating that apart from all the five levels being tapped, there would also be a mastery of progression from simpler category acting as a prerequisite to the more complex thinking following the BCD conceptualisation of Krathwohl (2017). The result challenges the study of Ambawati & Ardi (2019) and Juan & Chao (2015) that SGs can support lower-order thinking skills. Meanwhile, the findings of the study are more crudely linked and in congruence with Thomas (2002) who claimed that higher-order skills can be facilitated which eventually led to emotion, attitude, and behavioural changes. Such confounding alignment with earlier literature brings the conversation to the first main issue under investigation, which particular game element enhances specific cognitive thinking process.

In-game management acted as the main game element driver, displaying significant associations in facilitating applying, analysing, and evaluating cognitive processes. Fostering three thinking hierarchies is not surprising. The element activates collaborative space among players that entails effective communication. Studies in SG and simulation games show that collaborations that combine effective communication, analytical, evaluative and creative problem solving likely enhance higher-order cognitive outcomes (van Voorhis & Paris, 2019). Conversely, in-game management actively promote flexible decision-making (analysing and evaluating), solution-building (applying), and problem-solving (analysing and evaluating). Games that enhance problem-solving (Waeber et al., 2023) and decision-making skills (Cosme & Turchen, 2020) similarly provide positive knowledge absorption benefits.

Game events such as activating new infestation sites based on rainfall, topography, and human-mediated farm activities activated the cognitive domain, analysing. Game events being an open-ended content, scenarios that do not have single predetermined solution (Bengston et al., 2021), likely explains why only one cognitive process is promoted. Based on the rules, players when affected by game events can explore a variety of decisions, for instance, deciding between cleaning their boots to further stop the infestation or ignoring their active vector status for the rest of the game. There are still debates in the SG research community that open-ended content, despite enhancing collaboration (Bengston et al., 2021), too much game freedom can lead to difficulty in measuring educational impact (Waeber et al., 2023). In fact, participants emphasised that game events while adding extra layer of information source through complex thinking-inducing mechanisms, events can also be confusing and visually overwhelming. Overall, the findings that support events as analysing-inducing element is reasonable since players analyse game changes by breaking down information into components. The cognitive process entails comparing and contrasting (Anderson & Krathwohl, 2001; Bloom, 1956) that was exemplified when players assess where the new infestation sites are located prior to game event, or examining patterns of cause-and-effect connections such as when testers identify transmission factors.

Trivia displayed content absorption through application (applying as cognitive process). This is a surprising result since trivia is expected to fortify basic factual recall and understand concepts in the game. Conversely, trivia provided foundational knowledge about *Pc* but it is probable that the association with applying is in congruence with quizzes whenever players clear the questions, highlighting the roles of prompt design. Prompt design refers to triggers that guide player attention toward learning objectives (Gee, 2003). For instance, the sequencing of trivia items before quizzes enabled players to immediately transfer the facts into context-specific decision-making, thereby, reinforcing application. The translation of trivia's game design aligns with BCD's definition of the use of knowledge in new situations and contexts (Anderson & Krathwohl, 2001; Bloom, 1956). The timed and deliberate sequencing support Plass et al. (2015) and Mayer (2014) who proposed that well-sequenced instructional cues can bridge lower to higher-order processes, thereby explaining why players perceived trivia as a tool that bolsters knowledge application than mere absorption.

Quiz as an effective game element failed to reach statistical significance to any of the cognitive processes. Hence, the study cannot conclude the impacts of quizzes in teaching specific learning contents about *Pc* as well as the cognitive process the element fosters. However, it is worth-emphasising that quiz alongside trivia was cited several times post-game, claiming that the element assisted in sustainability thinking. Simply disregarding quizzes for not reaching statistical association with any of the cognitive processes would be a reductionist move. Quizzes, potentially, have manifested different forms of integration with other game elements, hence, acting as a support element to sharpen the five cognitive thinking skills. This can be further explained by the element serving as a tailored quick assessment on conceptual integration and content absorption by players, marrying the foundational knowledge support trivia offers. The formative assessment role of quizzes aligns with some existing body of literature. Embedded checks of understanding like quizzes support learning and improve student interests (Shute, 2011; Wag, 2008; Buchanan, 2000), aids in memory retention (Roediger et al., 2006), and "discourage task-irrelevant mind-wandering" (Szpunar et al., 2013, p. 6313). Through quiz, the phenomenon called "testing effect" was exhibited in the game. The effect claims that taking memory test works beyond assessment of what students know but also enhances retention (Roediger et al., 2006) and recall accuracy (Taveira-Gomes et al., 2015); a clear reflection of how quizzes in Silent Spread served as an information preservation tool. A respondent remarked, "It [the quiz] acted as a reminder of the things I have forgotten, thus, it made my learning experience more fun.". Moreover, such association of players can be linked to the evidence that SGs reduce test anxiety, thereby, increasing fun and engagement as compared to traditional instruction materials (Germa, et al., 2020; Borit et al., 2020; Metz, et al., 2011). Meshing of information within the trivia-to-quiz flow encouraged respondents to pay close attention to the learning content, prepare for the questions later in the game, and foster a sense of satisfaction. Quizzes also unravelled opportunities for players to discuss their own understanding and raise analytical arguments with one another. This aligns with the study demonstrating that increased scores in quizzes can be attributed to peer influence from knowledgeable students, and results from gains in understanding whenever questions are discussed among neighbours (Smith et al., 2009). Similarly, game-based learning enhances soft skills such as teamwork (Gee, 2004) that improves learning retention and socialisation (Squire, 2008; Van Eck, 2006).

6.2.2 More than just a frequency count

In-game performance reveals interesting results. When answering quizzes, players' mistakes increased when faced with challenges that capture middle-order thinking skills (analysing) and then declined again, meaning players started performing well, across higher-order thinking skills (evaluating) (Figure 22). The explanation to this trend circles back to the very definition of analysing in the BCD framework. The performance fluctuations in the middle tier support the work that analytical capabilities require learners to go beyond mere fact recall, instead demand more relationship-identifying skills (Krathwohl, 2002). Analytical tasks are often proven more challenging because they are less directly supported by memorisation, instead warrant abstract cognitive processing and reasoning (Anderson & Krathwohl, 2001). Players likely did not adapt quick enough from the basic fact recall and comprehension presented in quizzes on Level 1 and Level 2. The question that most players fail to clear is the manner of presentation the disease transmission (i.e. treasure box) was shown and then players were immediately asked to identify the spread mechanisms without giving proper time to process the data. A player even mentioned, "I think we did not see enough what happened.". Time can be a worthy opponent which is counter-intuitive to explore learning because it channels players to focus on time rather than the learning content and impact (Menconi, et al., 2025). A study shows that adaptive scaffolding improves speed, lowers cognitive load, thereby, produces more efficient performance (Faber et al., 2024), which supports the bridging from basic fact recall and increase cognitive demands. Meanwhile, the trend where players started performing better again when engaging with evaluating is likely supported with more concrete scenarios and decision-making tasks. For instance, quizzes designed to facilitate evaluative skills present scenarios embedded in the questions or options (Annex I). Providing more support on quizzes that embellish evaluative skills is the exact illustration of adaptive scaffolding (Faber et al., 2024) which was likely absent in questions designed to increase analytical thinking.

Thus, the findings highlight that the bottleneck in learning is not necessarily the cognitive demands themselves, but the lack of scaffolding at the transition points in between cognitive thinking skills. This is particularly important for SG development twofold. First, games should be designed to recognise analytical skill as more than a just transition stage to higher-order thinking. Secondly, the fluctuation exacerbates the need to embed scaffolding to sustain cognitive progression within the game. If SG scholarship would transcend from KA to knowledge application-centred future, games should be designed where stages should not just be fragile connection points, hoping to link different cognitive demands, rather, should complementarily embellishes each thinking processes. These recommendations can be more clearly defined in the following section.

6.2.3 Small contributory effects could lead to improved learning

The interpretation of total effects flags important empirical observation. Trivia did not exert statistical significance to general information (Figure 23), yet when mediators such as applying and understanding aggregated, trivia's overall impact becomes appreciably stronger as shown in the total effects analysis (Figure 25, Table 10). Similarly, game events demonstrated moderate total effect on management practices (Figure 25), however, the direct path did not reach statistical associations (Figure 23). First of all, this trend exhibited by trivia and game events was later flagged along the total effects examination. In PLS-SEM literature, total effects capture the broader picture of an exogenous constructs in achieving the final endogenous outcome (Hair et al., 2022).

To unpack the observation, the case of trivia likely underscores that small contributory effects across multiple learning processes can accumulate into a meaningful learning facilitation, even when no single pathway stands out on its own. This was repeated mentioned during the card-sorting activity (Table 11) emphasising that players need all four game elements to understand the basic of Pc (environmental pillar), the need to tackle the infestation problem through multi-stakeholder engagement (social sustainability pillar), and the sustenance and trade-offs between acorn and Iberian pig production (economic pillar). Moreover, the illustrative case of game events highlights how learning elements may exert influence through a diffuse cognitive mechanism instead of a single, and linear connection. Zhao et al. (2010) pointed out that mediation should not be confined to individual strong paths (Figure 24). Hence, even though the direct pathway from game events to management comprehension is lacking, the moderate total effects was contributed with multiple mediating processes. This again supports the similar case raised about trivia; small contributory support of multiple thinking skills could lead to improved learning.

6.2.4 Cognitive Sustainability Compass as a tool for reflective sustainability thinking

Debriefing is an important part of gameplay (Crookall, 2014). Cognitive Sustainability Compass, as the debriefing tool to recollect memories of game interaction, demonstrates that the integration of game elements can assist players to reflect outside the game environment, briefly answering the second research inquiry. This is particularly insightful because studies on knowledge transfer in agroecology show comparatively low average scores in pre- and post-surveys after playing a SG (i.e. SEGAE) (De Graeuwe, et al., 2024; Jouan & De Graeuw, 2020). The card-sorting activity clearly exhibited that participants articulated their learning to wider sustainability issues, suggesting that the learning transcend beyond the intended five learning hierarchies and strengthened even the highest thinking process, creating. This suggests that despite earlier studies claiming the low-test performances with SGs as the research intervention, assessments should come in other forms as learnings can manifest differently.

The findings mean two important contributions in SG and sustainability education. Firstly, the notion that SGs are not sufficient to tackle holistic learning approach in sustainability philosophy (Stanistas, et al., 2019) is not entirely accurate. For the sake of argumentation, indeed, the compass activity is an external evaluation tool and not part of Silent Spread. However, the clear proof of players categorising sustainability concepts, debating on the relevance and overlap among ideas, and even explaining cause and effect and trade-offs between pillars solidified SGs capabilities as a game-based learning tool to activate system thinking (Binkey et al., 2014). This elevates the post-game activities as a crucial part of learning assessment, supporting the proposal of Stanistas, et al., (2019) to use tangible and practical solution to address the "Achilles' heel' of modern education systems in sustainable development. Secondly, the Cognitive Sustainability Compass activity exhibited that sustainability thinking is not just technical comprehension, but the ability to categorise concepts into disciplinary silos. The mechanisms that occurred between in-game, and post-game reflection lever the saliency of heuristic learning. In the cognitive niche, humans are more capable of answering complex problems when contextualised and digested to narrow specialised ones (Boyd, Richerson, Henrich, 2011). Such concept modularisation enabled players to percolate larger concept such as economic impacts of infestation to smaller subcomponents like the cost and benefit of early transmission detecting and immediate solution implementation to reduce economic loss.

The concentration of sustainable concept reflection gravitating towards social sustainability pillars is challenging the anticipated results. Silent Spread is inherently a game that embeds niche, technical, and life-science centred instructional material. However, participants articulated concepts that fall mostly within the social compass than environmental and economic sections (Figure 26). Emergent themes such as collaborative problem-solving, increased connection to rural realities, knowledge-sharing, and attitude and even behavioural changes mirror the broader landscape of social learning. Research shows that collaborative SGs enhance social learning (Den Haan & Van der Voort, 2018), or the changes in the understanding of a system or problem through participatory setting (Reed et al., 2010). Thus, the prominence in social lens reflections is likely facilitated by the multiplayer settings, collaborative game rules and mechanics, and collective infestation problem-solving, rather than the technical learning content. This is strengthened by the earlier study that shows social sustainability discussions can emerge even without clear connections to ecological concerns, which is termed as a conceptual slippage (Isgren & Longo, 2024). Conceptual slippage in this context is defined as the performative backdrop of biophysical systems to investigate social issues, thereby, explaining why social sustainability concepts emerged more prominently than the anticipated environmental-centred discussions. Moreover, the strong emphasis on the collaborative play and sustainability reflection mirrors studies linking game-based learning with soft skill development such as teamwork (Gee, 2004), socialisation improvement (Squire, 2008), and shifting of self-centred game strategies to more cooperative in-game actions (Irabor, et al., 2024). The trivia identified as the most useful element to inspire social sustainability (See Table) is likely a result of players focusing on the application of knowledge they gained from the trivia, instead of simply understanding or remembering facts, in turn, aligning to the statistical correspondence of trivia with the cognitive thinking process, applying (See Table). Moreover, digital games are designed to manifest social interactions within an abstract and simulated digital environment. Existing literature claims that games' immersive narrative and interactive nature heightens awareness and attitude change on certain topics (Ouariachi, Olvera-Lobo, & Gutiérrez-Pérez, 2017). Because of this, gamers, as expected, mirrored the intended designs to facilitate interaction. This results to players seeing Silent Spread as a tool that corroborates collaborative learning and increasing awareness on societal issues, thereby, explaining the concentration on social sustainability foundations during post-game reflections.

Players heavily discussing environmental pillars and concepts is in line with the expectations of the study, albeit, not emerging as the most commonly discussed sustainability dimension as hypothesised. In general, the compass-making session positioned the game as particularly useful in linking technical knowledge of *Pc* management with broader ecological challenges. Emerging themes include biodiversity loss, IPM, understanding spread mechanisms and the ecology of *Pc*. Results show that game events were the most frequently used element when players discussed environmental sustainability. Game events such as treasure boxes may have contributed immensely on the players' reflections about spread mechanism. For instance, post-game responses mentioned that game events acted as additional layers of information, such as the roles of unclean boots, rainfall, topography, human- and invertebrate-mediated activities. All of these cues lead to increased environmental-focused systems thinking of the players. The results corroborate with a similar study on systems thinking where players demonstrated increased perceptions of ability to interconnect across environmental domains when engaging with SG (i.e. food, energy and water system) (Sajjadi et al., 2022). Moreover, studies show that experiential game-based learning provides a 'glass box' approaches wherein players are supported in developing complex system competencies (Emihovich, 2024). This approach was exemplified when players are able to connect how biodiversity loss is a complex and interrelated problem that involves collective and communal action. Trivia and quizzes strengthened the respondent's environmental inclination, too. The two game elements are embedded with cues such as the scientific words, technical information, statistics, and literature citations that potentially prompted the players overall understanding about IPM and the ecology of Pc. Earlier studies demonstrate that typographical cues improve recall and learning effectiveness (Roberts, 2016). Furthermore, the findings are consistent with a systematic review that engagements with real-world problem simulations and learning-by-doing design effectively contributes in knowledge and even attitude shift for environmental stewardship (Tan & Nurul-Asna, 2023).

Lastly, players reiterated on the key trade-off mechanisms between the tree disease and its effect to acorn production and Iberian pig industry. The sustainability compass-making activity clearly demonstrated that participants stressed the role of balancing costs with benefits to fight the infestation, making the pest management a crucial dimension in rural livelihood sustenance. The themes that have emerged aligns with studies demonstrating that role-playing games can effectively facilitate social learning around trade-off mechanisms (Moreau, Barnaud & Mathevet, 2019), which echoes the gamers' proven understanding of coupled economic and ecological benefits. Similarly, repeated gameplay also show evidence that resource sharing and adaptive planning can lead to easier grasping of short-term gains, and long-term sustainable outcomes (Irabor et al., 2025). Based on the activity, trivia also emerged as the most useful game element assisted in social sustainability pillar reflections, which is at par from the other three. Surprisingly, quiz was cited less on this sustainability domain which is in contrast with the earlier claims that trivia and quizzes go hand-in-hand to fortify knowledge absorption and comprehension check. This can be explained by the fact that trivia provides straight-to-the point information with typographic cues as support (e.g. underlined and bold words) while quizzes demand more cognitive effort for players to absorb knowledge, despite being a useful technical comprehension check tool according to responses.

6.2.5 Causal and spillover reflections in sustainability thinking

Participants' reflection mirrors the consistent sustainability education research that key competencies such as systems thinking, and strategic solution-building cuts across multiple domains (Wiek et al., 2011). Naturally, well-designed sustainability-related activities elicit all the three pillars; this is not the main contribution of the qualitative strand of the study. Instead, two relationships are worth-exploring, namely the causal and spillover effects in sustainability thinking postgame.

First of all, SGs are evaluated using pre- and post-tests, self-reported competencies, or behavioural inclinations (Plass et al., 2015). However, narrating causal linkages or perceive spillover effects are rarely used to measure learning outcomes, increasing the novelty of the study. By situating causal and spillover reasoning within the Cognitive Sustainability Compass activity, the research extends the notion that players' post-game reflections as a debriefing exercise can trace multi-directional relationships in sustainability thinking. This is particularly important because the emergent cognitive patterns had remained invisible in traditional survey and quiz-based assessments. Cognitive Sustainability Compass enriches the depth and systemic reflection of learning outcomes rather than simply ticking boxes and choosing numbers to evaluate their experience.

Secondly, the causal reflections warrant further unpacking. Players repeatedly mentioned cause-and-effect relationships. For instance, gamers connected tree mortality to acorn shortages, affecting the downstream effects to the Iberian pic production and economy. Similarly, reflections stress how farm-level decisions can cascade into biodiversity outcomes. Such interconnections made by players illustrate the important shift from basic fact recall, evaluation of scenarios, or applying management solutions, rather, players tapped systems-oriented line of thinking post-gameplay. This confirms that developing systems thinking competence (Wiek et al., 2011) is possible in SG-oriented learning approach. Meanwhile, spillover effects were demonstrated when players first described their insights from one sustainability pillar and informed the effects into another. For instance, biodiversity loss is a consequence not only affects the environmental arena, but also concerns the social and economic issue tied to the need for collective effort to fight the infestation and sustain local economy, respectively. In SG research, cascading effects through immersive scenarios are common, which in this case, likely blurs the disciplinary boundaries of the pillars. This results to prompting learners to see an integrated system of challenges rather than separate silos (Plass et al., 2015). Such emphasis made by players themselves elevates that the game alongside the Cognitive Sustainability Compass fostered a learning space for holistic sustainability thinking, that is, otherwise, as previously mentioned, would have remained hidden.

The two types of relationship-building could just be some of the possible emergent reflections the Cognitive Sustainability Compass can assist with. The tool does not only demonstrate its power as a new and unique tool, but as aa forward-thinking research arena that is worth-exploring. Similarly, SG research and development enabling the perceiving of interdependencies, cascading effects, and cross pillar trade-offs deserve their own scholarly space. Games that articulate these opportunities either in-game or as a post-game reflection enriches ways how sustainability thinking can be activated among university-level students. SGs are no longer instructional materials, rather, can act as 'cognitive laboratories' where learners can practice systems thinking through gamified environments while exploring complex challenges such as the invisible battles in Pc infestation, or the wider sustainability arena.

6.3 Implications of the Study

The methodological implication of the study is to gear the SG scholarship from assessing game-based learning as a tool to measure learning acquisition (or KA) and start further examining how SGs can teach players to apply their knowledge within and during gameplay. The immense use of SG to impart knowledge is at an impasse; 21st century requires 21st century skills. Silent Spread clearly demonstrated that players are capable to harness and illustrate creativity, critical thinking, problem-solving, solution-building, and systems thinking. The manifestation of such thinking skills is another proof that SGs capabilities should be extended to knowledge application, and departing from the reductionist lens that these innovative games are merely for factual recall or basic comprehension. SGs should no longer be situated within the limits of traditional learning outcomes, rather act as a simulation where contexts such as creativity, critical thinking and systems reasoning are sharpened.

The study also challenges the lens of BCD. The hierarchical model of ascending cognitive processes from basic to complex thinking is obsolete. Results reveal that players view the individualised game elements not as a single piece in the game, rather complementary units that are capable of creating a system. The theoretical implication, therefore, highlights that SGs capabilities to facilitate thinking processes requires revisiting wherein hierarchal thinking should be replaced with systemic thinking that reflects the complex ways KA and knowledge application manifests in concepts like sustainability and situations where collaborative problem-solving is needed.

Lastly, the practical implications marry the methodological inferences. The results are particularly applicable to educators who are elevating their curricula to tackle 21st century skills development. Beyond teaching *Pc* infestation management, games designed to teach future agroforestry and rural development professionals should aspire for game mechanics that target facilitating systems thinking where complex causal relationships within systems are holistically perceived (Arnold & Wade, 2015). Additionally, beyond higher-order thinking skills, games should target sharpening proactive decision-making, creative solution-building, and critical sustainability reasoning beyond the game limits.

It is important to address the limitations the research suffered from. In terms of methodological constraints, the small sample size and incongruencies in model fit are worth-flagging, despite the exploratory and variance-based nature of the study (See 5.3.5). Additionally, the software used, Genially, has limited capacities as a game development tool. Functionalities such as a) automation in feedback and reward system, b) the inability to access by multiplayer set-up that are remotely separated, as well as c) the technical software and hardware resources available to the researcher may have contributed to the overall game experience, frustration, disinterest, and confusion among players.

7. Conclusion

The output of the research contributes to the growing recognition that SGs are interactive and effective pedagogical tool that can shape several thinking processes. However, despite being widely studied, persistent gaps exist, limiting the full potential of SGs as an agent that harnesses skills necessary for the 21st century. The often-overlooked invisible battles in fighting invasive root pathogens serve as the backdrop, contextualising *Phytophthora cinnamomi* into a digital board game designed to teach university-level students about disease transmission mechanisms and management practices to stop further infestation.

This research sets out a) to examine whether a digital SG could facilitate university student's KA about *Pc* across different cognitive thinking processes following BCD, b) to identify which specific game elements most effectively enhance such thinking processes, and c) explore whether a post-game reflective activity could inspire broader sustainability reflections facilitated by the Cognitive Sustainability Compass. Tackling the first objective, Silent Spread was effective in fostering middle- to higher-order thinking processes, where concentration gravitates toward applying, analysing, and evaluating. The findings indicate that the game went beyond the game intent of simply teaching spread mechanisms and management solutions, rather facilitated such advanced thinking abilities, in turn equipping players to relate the knowledge they gained to complex problem-solving. Concerning the second objective, in-game management consistently proved its strongest facilitator role in KA, particularly in three cognitive processes, while game events contributed to deeper learner through analytical capacities, and trivia bolstering application-driven actions during the gameplay. Collectively, these insights affirm that not all game elements equally support cognitive skill acquisition, instead their pedagogical utility depends on interaction with content and learner experience. Lastly, the Cognitive Sustainability Compass revealed that participants, indeed, were able to transfer the players' newly-acquired knowledge in broader challenges and systemic thinking-driven post-game reflections. Themes such as collaboration, experiential learning, and increased connection to rural realities dominate the social sustainability pillars. Environment and economic pillars were explored to a lesser extent.

Consolidating all the key findings in the study, the research stresses the tension that games are no longer exhibitor of basic factual recall and surface level comprehension. Silent Spread demonstrates that both within and outside game play, SGs become a safe and navigable virtual environment for critical, collaborative and more importantly, sustainability thinking. The different yet complementary manifestations of in-game performances and sustainability conceptualisations demonstrated by players invite reframing: that is SGs no longer supplement the widely-studied knowledge absorption (or KA) but evolves into a tool that fosters knowledge application. This shift demands further exploration to advance SG scholarship. To the author's best knowledge, empirically simultaneously investigating four game elements to assess the five cognitive thinking processes from BCD and integrating sustainability compass mapping post-game play to capture the highest thinking hierarchy was done for the first time. This novelty proves that in-game performance analysis is just as crucial as post-game reflective evaluations to fully maximise the power of SGs in agroforestry and the wider sustainability arena.

Future research may explore increasing the sample size, potentially achieving significant results in group differences that the current study fails to attain. Theoretically, the conceptual model used also require revisiting, be it adding or omitting constructs to improve model fit. SG enthusiasts can also explore the nuances between attrition and game mechanics. Attrition is defined as the gradual loss of interest during the intervention (Lumsden et al., 2017), which was remarked by the respondents, yet the current study does not empirically address. Similarly, players exhibited the "testing effect", wherein students typically exhibit enhanced learning but when higher cognitive demand arises, their performance diminishes. SG developers can also extract the positive and negative responses of players, contributing to the ever-evolving nexus of game design, assessment models, and overall experiential learning. While the cognitive compass making shows promising success in internalising sustainability concepts, making the post-reflection a mandatory data-gathering assessment would strengthen the knowledge application manifestation outside gameplay and beyond the game limits.

Overall, Silent Spread presents a promising tool to train future of rural development professionals, policymakers, forest engineers, and farmers who are future proof, capable of navigating complexities in agroecology and sustainability transitions. The creativity and innovation the game embeds has the potential to transform passive learners into proactive decision makers, critical thinkers, and creative problem solvers.

"Just because the spread is silent, our learning does not have to be."

References:

Abt, C. C. (1987). *Serious games*. University press of America.

Anderson, L. W., & Krathwohl, D. R. (Eds.). (2001). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives*. Longman.

Albrecht, A., & Kandji, S. T. (2003). Carbon sequestration in tropical agroforestry systems. *Agriculture, ecosystems & environment*, *99*(1-3), 15-27.

Alhazmi, A. K., & Rahman, A. A. (2012, October). Why LMS failed to support student learning in higher education institutions. In *2012 IEEE Symposium on e-learning, e-management and e-services* (pp. 1-5). IEEE.

Altomari, L., Altomari, N., & Iazzolino, G. (2023). Gamification and soft skills assessment in the development of a serious game: design and feasibility pilot study. *JMIR serious games*, *11*(1), e45436.

Axelrod, R. (1980). Effective choice in the prisoner's dilemma. *Journal of conflict resolution*, *24*(1), 3-25.

Baranowski, T., Baranowski, J., Thompson, D., Buday, R., Jago, R., Griffith, M. J., ... & Watson, K. B. (2011). Video game play, child diet, and physical activity behavior change: A randomized clinical trial. *American journal of preventive medicine*, *40*(1), 33-38.

Baker, E. L. & Mayer, R. E. (1999) Computer-based assessment of problem solving, Computers in Human Behavior, 15, 269–282.

Batson, A., & Coleman, M. (2008). *CALEDON: Making a game of forest pathology to increase awareness of tree diseases, pests, and production*. The Plant Health Instructor. https://doi.org/10.1094/PHI-T-2018-0814-01

Beale, I. L., Kato, P. M., Marin-Bowling, V. M., Guthrie, N., & Cole, S. W. (2007). Improvement in cancer-related knowledge following use of a psychoeducational video game for adolescents and young adults with cancer. *Journal of Adolescent Health*, *41*(3), 263-270.

Bloom, B. S., Engelhart, M. D., Furst, E. J., Hill, W. H., & Krathwohl, D. R. (1956). Handbook I: cognitive domain. *New York: David McKay*, 483-498.

Bolton, G. E., & Ockenfels, A. (2000). ERC: A theory of equity, reciprocity, and competition. *American economic review*, *91*(1), 166-193.

Boulestreau, Y., Casagrande, M., & Navarrete, M. (2023). A method to design coupled innovations for the agroecological transition. Implementation for soil health management in Provencal sheltered vegetable systems. *Agricultural Systems*, *212*, 103752.

Boyd, R., Richerson, P. J., & Henrich, J. (2011). The cultural niche: Why social learning is essential for human adaptation. *Proceedings of the National Academy of Sciences*, *108*(supplement_2), 10918-10925.

Boyle, E., Connolly, T. M., & Hainey, T. (2011). The role of psychology in understanding the impact of computer games. *Entertainment computing*, *2*(2), 69-74.

Boyle, E. A., Hainey, T., Connolly, T. M., Gray, G., Earp, J., Ott, M., ... & Pereira, J. (2016). An update to the systematic literature review of empirical evidence of the impacts and outcomes of computer games and serious games. *Computers & Education*, *94*, 178-192.

Buchanan, L., Wolanczyk, F., & Zinghini, F. (2011). Blending bloom's taxonomy and serious game design. In *Proceedings of the International Conference on Security and Management (SAM)* (p. 1). The Steering Committee of The World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp).

Byun, J., & Loh, C. S. (2015). Audial engagement: Effects of game sound on learner engagement in digital game-based learning environments. *Computers in Human Behavior*, *46*, 129-138.

Calsamiglia, S., Espinosa, G., Vera, G., Ferret, A., & Castillejos, L. (2020). A virtual dairy herd as a tool to teach dairy production and management. *Journal of dairy science*, *103*(3), 2896-2905.

Cardillo, E., Abad, E., & Meyer, S. (2020). Spatio-temporal analysis at landscape scale of the Iberian oak decline epidemic caused by Phytophthora cinnamomi. *bioRxiv*, 2020-03.

Carroll, J. M. (1997). Human–computer interaction: Psychology as a science of design. *International journal of human-computer studies*, *46*(4), 501-522.

Cheung, G. W., Cooper-Thomas, H. D., Lau, R. S., & Wang, L. C. (2024). Reporting reliability, convergent and discriminant validity with structural equation modeling: A review and best-practice recommendations. *Asia pacific journal of management*, *41*(2), 745-783.

Cheng, M. T., Chen, J. H., Chu, S. J., & Chen, S. Y. (2015). The use of serious games in science education: a review of selected empirical research from 2002 to 2013. *Journal of computers in education*, *2*(3), 353-375.

Cardillo, E., Abad, E., & Meyer, S. (2021). Iberian oak decline caused by Phytophthora cinnamomi: A spatiotemporal analysis incorporating the effect of host heterogeneities at landscape scale. *Forest Pathology*, *51*(2), e12667.

Coleman, M. (2017). Online game changer for tree health.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum.

Connolly, T. M., Boyle, E. A., MacArthur, E., Hainey, T., & Boyle, J. M. (2012). A systematic literature review of empirical evidence on computer games and serious games. *Computers & education*, *59*(2), 661-686.

Cosme Jr, L., Turchen, L. M., & Guedes, R. N. C. (2020). Insect world: game-based learning as a strategy for teaching entomology. *The American Biology Teacher*, *82*(4), 210-215.
Czaika, E., & Selin, N. E. (2017). Model use in sustainability policy making: An experimental study. *Environmental Modelling & Software*, *98*, 54-62.

Drachen, A., Seif El-Nasr, M., & Canossa, A. (2013). Game analytics–the basics. In *Game analytics: Maximizing the value of player data* (pp. 13-40). London: Springer London.

Esposito Vinzi, V., & Russolillo, G. (2013). Partial least squares algorithms and methods. *Wiley Interdisciplinary Reviews: Computational Statistics*, *5*(1), 1-19.

de la Vega, G. J., Falconaro, A. C., Soria, L., & Corley, J. C. (2022). Integrated pest management education: a video-game to improve management of Drosophila suzukii, soft-skin fruit pest. *Neotropical Entomology*, *51*(5), 801-807.

De Graeuwe D'Aoust, M., Dumont, B., & Maréchal, K. (2024). Quantifying agroecology learning with the SErious Game for AgroEcology (SEGAE) in a 4-hour lesson. In *15th IFSA conference*.

Den Haan, R. J., & Van der Voort, M. C. (2018). On evaluating social learning outcomes of serious games to collaboratively address sustainability problems: A literature review. *Sustainability*, *10*(12), 4529.

Dernat, S., Vollet, D., Cayre, P., Dumont, B., & Rigolot, C. (2019, June). Accompanying the collective construction of a plan for the future. The case of a collaborative and territorialized process for the actors of the PDO cheese 'Fourme de Montbrison'(Loire, France). In *Agricultural Education and Extension Tuned on Innovation for Sustainability. Experiences and perspectives, Proceedings of the 24th European Seminar on Extension and Education* (pp. 18-21).

Dernat, S., Grillot, M., Andreotti, F., & Martel, G. (2025). A sustainable game changer? Systematic review of serious games used for agriculture and research agenda. *Agricultural Systems* , *222* , 104178.

de Rosa, F., & De Gloria, A. (2021). Design methodology of analytical games for knowledge acquisition. *International Journal of Serious Games*, *8*(4), 3-23.

Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). *From game design elements to gamefulness: Defining "gamification"*. In Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments (pp. 9–15). ACM. https://doi.org/10.1145/2181037.2181040

Dieterle, E., Dede, C., & Schrier, K. (2007). " Neomillennial" Learning Styles Propagated by Wireless Handheld Devices. In *Ubiquitous and pervasive knowledge and learning management: Semantics, social networking and new media to their full potential* (pp. 35-66). IGI Global Scientific Publishing.

Driscoll, M. P. (1994). *Psychology of learning for instruction*. Allyn & Bacon.

Docherty, C. W. (2020). Scoping the Potential Use of Serious Games for Public Engagement with Tree and Plant Health.

Dourmad, J. Y., Adji, K., Boulestreau-Boulay, A. L., Emeraud, L., & Espagnol, S. (2013, August). A 3D-serious game for teaching the environmental sustainability of pig farming systems. In *64. Annual Meeting of the European Federation of Animal Science (EAAP)* (Vol. 19, pp. 660-p). Wageningen Academic Publishers.

Dunstan, W. A., Rudman, T., Shearer, B. L., Moore, N. A., Paap, T., Calver, M. C., ... & Hardy, G. E. S. J. (2010). Containment and spot eradication of a highly destructive, invasive plant pathogen (Phytophthora cinnamomi) in natural ecosystems. *Biological Invasions*, *12*(4), 913-925.

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M. A., Justes, E., ... & Sarthou, J. P. (2015). How to implement biodiversity-based agriculture to enhance ecosystem services: a review. *Agronomy for sustainable development*, *35*, 1259-1281.

Espinosa-Curiel, I. E., & de Alba-Chávez, C. A. G. (2024). Serious video games for agricultural learning: scoping review. *IEEE Transactions on Learning Technologies*, *17*, 1155-1169.

Esposito Vinzi, V., & Russolillo, G. (2013). Partial least squares algorithms and methods. *Wiley Interdisciplinary Reviews: Computational Statistics*, *5*(1), 1-19.

Faber, T. J. E., Dankbaar, M. E. W., van den Broek, W., & Bruinink, L. (2024). *Effects of adaptive scaffolding on performance, cognitive load and engagement in game-based learning: A randomized controlled trial*. BMC Medical Education, 24(1), Article 5698. https://doi.org/10.1186/s12909-024-05698-3

Francis, C. A., Lieblein, G., Breland, T. A., Salomonsson, L., Geber, U., Sriskandarajah, N., & Langer, V. (2008). Transdisciplinary research for a sustainable agriculture and food sector. *Agronomy Journal*, *100*(3), 771-776.

Francis, C. A., Jordan, N., Porter, P., Breland, T. A., Lieblein, G., Salomonsson, L., ... & Langer, V. (2011). Innovative education in agroecology: Experiential learning for a sustainable agriculture. *Critical Reviews in Plant Sciences*, *30*(1-2), 226-237.

Foppe, S., & von Wehrden, H. (2025). A leverage point perspective on serious games for sustainability transformation: a systematic literature review. *Sustainability Science*, *20*(1), 269-286.

Gabay, M., & Rekola, M. (2019). Forests, peaceful and inclusive societies, reduced inequality, education, and inclusive institutions at all levels: Background study prepared for the fourteenth session of the United Nations Forum on Forests.

Garrity, D. P. (2004). Agroforestry and the achievement of the Millennium Development Goals. *Agroforestry systems*, *61*, 5-17.

Gee, J. P. (2005). Learning by design: Good video games as learning machines. *E-learning and Digital Media*, *2*(1), 5-16.

Gee, J. P. (2003). What video games have to teach us about learning and literacy. *Computers in entertainment (CIE)*, *1*(1), 20-20.

Gil-Pelegrín, E., Peguero-Pina, J. J., & Sancho-Knapik, D. (Eds.). (2017). *Oaks physiological ecology: Exploring the functional diversity of genus Quercus L.* Cham: Springer International Publishing. Retrieved from http://link.springer.com/10.1007/978-3-319-69099-5 (Accessed April 12, 2025).

Goodison, T. (2001). The implementation of e-learning in uk higher education. In *EdMedia+ Innovate Learning* (pp. 613-618). Association for the Advancement of Computing in Education (AACE).

Gros, B. (2007). Digital games in education: The design of games-based learning environments. *Journal of research on technology in education*, *40*(1), 23-38.

Guest, G., MacQueen, K. M., & Namey, E. E. (2011). *Applied thematic analysis*. sage publications.

Guillén-Nieto, V., & Aleson-Carbonell, M. (2012). Serious games and learning effectiveness: The case of It'sa Deal!. *Computers & Education*, *58*(1), 435-448.

Hair, J. F., Hult, G. T. M., Ringle, C. M., & Sarstedt, M. (2021). *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)* (3rd ed.). Sage Publications.

Hair Jr, J. F., Howard, M. C., & Nitzl, C. (2020). Assessing measurement model quality in PLS-SEM using confirmatory composite analysis. *Journal of business research*, *109*, 101-110.

Hair, J., & Alamer, A. (2022). Partial Least Squares Structural Equation Modeling (PLS-SEM) in second language and education research: Guidelines using an applied example. *Research Methods in Applied Linguistics*, *1*(3), 100027.

Hair, J. F., Hult, G. T. M., Ringle, C. M., & Sarstedt, M. (2022). *A primer on partial least squares structural equation modeling (PLS-SEM)* (3rd ed.). SAGE Publications.

Hämäläinen, R. (2011). Using a game environment to foster collaborative learning: a design-based study. *Technology, Pedagogy and Education*, *20*(1), 61-78.

Hardham, A. R. (2005). Phytophthora cinnamomi. *Molecular plant pathology*, *6*(6), 589-604.

Hardham, A. R., & Blackman, L. M. (2018). Phytophthora cinnamomi. *Molecular plant pathology*, *19*(2), 260-285.

Helmberger, M. S., Lampasona, T. P., Lorenz, A. R., & Grieshop, M. J. (2022). Pest Quest: A Game of Strategy, Uncertainty, and Sticky Traps. *Journal of Integrated Pest Management*, *13*(1), 23.

Hernandez-Aguilera, J. N., Mauerman, M., Herrera, A., Vasilaky, K., Baethgen, W., Loboguerrero, A. M., ... & Osgood, D. (2020). Games and fieldwork in agriculture: A systematic review of the 21st century in economics and social science. *Games*, *11*(4), 47.

Hopwood, B., Mellor, M., & O'Brien, G. (2005). Sustainable development: mapping different approaches. *Sustainable development*, *13*(1), 38-52.

Hong, J. C., Hwang, M. Y., Tai, K. H., & Lin, P. H. (2021). The effects of intrinsic cognitive load and gameplay interest on flow experience reflecting performance progress in a Chinese remote association game. *Computer Assisted Language Learning*, *34*(3), 358-378.

Isnanda, R. G., Santosa, P. I., & Hartanto, R. (2023). The Effects of Surprising Events on Promoting Social Change in Unwinnable Persuasive Games. *International Journal of Serious Games*, *10*(1), 3-17.

Jouan, J., De Graeuwe, M., Carof, M., Baccar, R., Bareille, N., Bastian, S., ... & Godinot, O. (2020). Learning interdisciplinarity and systems approaches in agroecology: experience with the serious game SEGAE. *Sustainability*, *12*(11), 4351.

Jose, S. (2009). *Agroforestry for ecosystem services and environmental benefits: an overview* (pp. 1-10). Springer, Dordrecht.

Khaldi, A., Bouzidi, R., & Nader, F. (2023). Gamification of e-learning in higher education: a systematic literature review. *Smart Learning Environments*, *10*(1), 10.

Khelifa, R., & Mahdjoub, H. (2021). EcoDragons: a game for environmental education and public outreach. *Insects*, *12*(9), 776.

Kirkpatrick, D. L. (1994) Evaluating training programs: the four levels (San Francisco, CA, Berrett Koehler).

Klerkx, L., & Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?. *Global Food Security*, *24*, 100347.

Jouan, J., Carof, M., Baccar, R., Bareille, N., Bastian, S., Brogna, D., ... & Godinot, O. (2021). SEGAE: An online serious game to learn agroecology. *Agricultural Systems*, *191*, 103145.

Liu, B., Wu, Y., Xing, W., Cheng, G., & Guo, S. (2022). Exploring behavioural differences between certificate achievers and explorers in MOOCs. *Asia Pacific Journal of Education*, *42*(4), 802-814.

Lumivero. (2023). *NVivo (Version 14) [Computer software].* https://lumivero.com/products/nvivo/

Maharaj, S., & Greene, P. (2015). Gamification within plant health in the Forestry Commission.

Maniar, N. (2007, June). M-learning to teach university students. In *EdMedia+ Innovate Learning* (pp. 881-887). Association for the Advancement of Computing in Education (AACE).

Marley, S. C., & Levin, J. R. (2011). When are prescriptive statements in educational research justified?. *Educational Psychology Review*, *23*(2), 197-206.

Memon, M. A., Ramayah, T., Cheah, J. H., Ting, H., Chuah, F., & Cham, T. H. (2021). PLS-SEM statistical programs: a review. *Journal of Applied Structural Equation Modeling*, *5*(1), 1-14.

Berg Marklund, B., Engström, H., Hellkvist, M., & Backlund, P. (2019). What empirically based research tells us about game development. *The Computer Games Journal*, *8*(3), 179-198.

Martin, L., & Martin, W. (2015). Modifying an information literacy game for outreach events. *Reference services review*, *43*(4), 643-655.

Marsh, T. (2010). Activity-based scenario design, development and assessment in serious games. In *Gaming and cognition: Theories and practice from the learning sciences* (pp. 213-226). IGI Global.

Marzano, M., Dandy, N., Bayliss, H. R., Porth, E., & Potter, C. (2017). Part of the solution? Stakeholder awareness, information and engagement in tree health issues. *Biological Invasions, 19*(11), 3307–3321. https://doi.org/10.1007/s10530-017-1412-7

Mayer, R. E. (Ed.). (2005). *The Cambridge handbook of multimedia learning*. Cambridge university press.

Marley, S. C., & Levin, J. R. (2011). When are prescriptive statements in educational research justified?. *Educational Psychology Review*, *23*(2), 197-206.

Memon, M. A., Ramayah, T., Cheah, J. H., Ting, H., Chuah, F., & Cham, T. H. (2021). PLS-SEM statistical programs: a review. *Journal of Applied Structural Equation Modeling*, *5*(1), 1-14.

Mbow, C., Smith, P., Skole, D., Duguma, L., & Bustamante, M. (2014). Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current opinion in Environmental sustainability*, *6*, 8-14.

Merrill, S. C., Koliba, C. J., Moegenburg, S. M., Zia, A., Parker, J., Sellnow, T., ... & Smith, J. M. (2019). Decision-making in livestock biosecurity practices amidst environmental and social uncertainty: evidence from an experimental game. *PloS one*, *14*(4), e0214500.

Michael, D., & Chen, S. (2006). *Serious games: Games that educate, train, and inform*. Thomson Course Technology.

Moreno, G., & Pulido, F. J. (2008). The functioning, management and persistence of dehesas. In A. Rigueiro-Rodríguez, J. McAdam, & M. R. Mosquera-Losada (Eds.), *Agroforestry in Europe* (pp. 127–160). Dordrecht: Springer Netherlands. Retrieved from http://link.springer.com/10.1007/978-1-4020-8272-6_7 (Accessed April 12, 2025).

Morgan, C. B., Merrill, S. C., Clark, E. M., Wolfson, J. A., & Trubek, A. B. (2024). A serious games methodology to test solutions for regional food systems inequities. *Journal of Rural Studies*, *110*, 103366.

Mosquera-Losada, M. R., Santiago-Freijanes, J. J., Rois-DíAz, M., Moreno, G., den Herder, M., Aldrey-Vázquez, J. A., ... & Rigueiro-Rodríguez, A. (2018). Agroforestry in Europe: A land management policy tool to combat climate change. *Land use policy*, *78*, 603-613.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853-858.

Nair, P. R., Kumar, B. M., Nair, V. D., Nair, P. R., Kumar, B. M., & Nair, V. D. (2021). Definition and concepts of agroforestry. *An introduction to agroforestry: Four decades of scientific developments*, 21-28.

Neuendorf, K. A. (2018). Content analysis and thematic analysis. In *Advanced research methods for applied psychology* (pp. 211-223). Routledge.

Neuendorf, K. A. (2018). Content analysis and thematic analysis. In *Advanced research methods for applied psychology* (pp. 211-223). Routledge.

Obikwelu, C., & Read, J. C. (2012). The serious game constructivist framework for children's learning. *Procedia Computer Science*, *15*, 32-37.

O'Neil, H. F., Wainess, R., & Baker, E. L. (2005). Classification of learning outcomes: Evidence from the computer games literature. *The Cirriculum Journal*, *16*(4), 455-474.

Ouariachi, T., Olvera-Lobo, M. D., & Gutiérrez-Pérez, J. (2019). Serious games and sustainability. In *Encyclopedia of Sustainability in Higher Education* (pp. 1-10). Springer, Cham.

Park, E., Cho, M., & Ki, C. S. (2009). Correct use of repeated measures analysis of variance. *The Korean journal of laboratory medicine*, *29*(1), 1-9.

Prada, U. G., Hernández, M. O., & Ibañez, J. S. (2020). Systems dynamics and serious video games in an appropriation strategy of a decision support system for small livestock farmers.

Plass, J. L., Homer, B. D., & Kinzer, C. K. (2015). Foundations of game-based learning. *Educational psychologist*, *50*(4), 258-283.

Radziszewski, K., Weichbroth, P., & Anacka, H. (2021). Greencoin: A proenvironmental action-reward system.

Ravyse, W. S., Seugnet Blignaut, A., Leendertz, V., & Woolner, A. (2017). Success factors for serious games to enhance learning: a systematic review. Virtual Reality, 21(1), 31-58.

Reed, M. S., Evely, A. C., Cundill, G., Fazey, I., Glass, J., Laing, A., ... & Stringer, L. C. (2010). What is social learning?. *Ecology and society*, *15*(4).

Ringle, C. M., Sarstedt, M., Mitchell, R., & Gudergan, S. P. (2023). *SmartPLS 4*. SmartPLS GmbH, http://www.smartpls.com
Robin, C., Smith, I., & Hansen, E. M. (2012). *Phytophthora cinnamomi: Species profile*. *Forest Phytophthoras, 2*(1). https://doi.org/10.5399/osu/fp.2.1.3041

Rouault, A., Perrin, A., Renaud-Gentié, C., Julien, S., & Jourjon, F. (2020). Using LCA in a participatory eco-design approach in agriculture: the example of vineyard management. *The International Journal of Life Cycle Assessment*, *25*, 1368-1383.

Rodríguez-Piñeros, S., Walji, K., Rekola, M., Owuor, J. A., Lehto, A., Tutu, S. A., & Giessen, L. (2020). Innovations in forest education: Insights from the best practices global competition. *Forest Policy and Economics*, *118*, 102260.

Rudebjer, P. G., Taylor, P., & Del Castillo, R. A. (2001). A guide to learning agroforestry. *Training and Education Report*, (51).

Ruta, M., Scioscia, F., Colucci, S., Di Sciascio, E., Di Noia, T., & Pinto, A. (2010). A knowledge-based framework for e-learning in heterogeneous pervasive environments. In *Multiplatform e-learning systems and technologies: Mobile devices for ubiquitous ICT-based education* (pp. 20-41). IGI Global.

Sales-Baptista, E., d'Abreu, M. C., & Ferraz-de-Oliveira, M. I. (2016). Overgrazing in the Montado? The need for monitoring grazing pressure at paddock scale. *Agroforestry Systems, 90*, 57–68. https://doi.org/10.1007/s10457-015-9826-1

Salvini, G., Van Paassen, A., Ligtenberg, A., Carrero, G. C., & Bregt, A. K. (2016). A role-playing game as a tool to facilitate social learning and collective action towards Climate Smart Agriculture: Lessons learned from Apuí, Brazil. *Environmental science & policy*, *63*, 113-121.

Sarin, R., & Wieland, A. (2016). Risk aversion for decisions under uncertainty: Are there gender differences?. *Journal of Behavioral and Experimental Economics*, *60*, 1-8.

Scanu, B., Linaldeddu, B. T., Deidda, A., & Jung, T. (2015). Diversity of Phytophthora species from declining Mediterranean maquis vegetation, including two new species, Phytophthora crassamura and P. ornamentata sp. nov. *PLoS One*, *10*(12), e0143234.

Sajeva, M., Kotta, J., Valonen, M., Korhonen, O., Kinnunen, P., Aalto, L., ... & Horne, P. (2024). Implementation of the Sustainability Compass: A Bottom-Up Social Learning Approach in Initial Pilot Studies. *Sustainability*, *16*(10), 4271.

ScienceDirect. (n.d.). *Game development*. In *Computer Science Topics*. Elsevier. Retrieved August 15, 2025, from https://www.sciencedirect.com/topics/computer-science/game-development

Shute, V. J., & Ventura, M. (2013). *Measuring and supporting learning in games: Stealth assessment*. MIT Press. https://doi.org/10.7551/mitpress/9589.001.0001.

Schoeneberger, M., Bentrup, G., De Gooijer, H., Soolanayakanahally, R., Sauer, T., Brandle, J., ... & Current, D. (2012). Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture. *Journal of Soil and Water Conservation*, *67*(5), 128A-136A.

Senado. (2010). *Ponencia de estudio sobre la protección del ecosistema de la dehesa* (Report No. 543/000009, p. 26). Senado.

Serrazina, S., Santos, C., Machado, H., Pesquita, C., Vicentini, R., Pais, M. S., ... & Costa, R. (2015). Castanea root transcriptome in response to Phytophthora cinnamomi challenge. *Tree genetics & genomes*, *11*, 1-19.

Sitzmann, T. (2011). A meta-analytic examination of the instructional effectiveness of computer-based simulation games. *Personnel Psychology, 64*(2), 489–528. https://doi.org/10.1111/j.1744-6570.2011.01190.x

Stanitsas, M., Kirytopoulos, K., & Vareilles, E. (2019). Facilitating sustainability transition through serious games: A systematic literature review. *Journal of cleaner production*, *208*, 924-936.

Sukajaya, N., Purnama, K. E., & Purnomo, M. H. (2015). Intelligent Classification of Learner's Cognitive Domain using Bayes Net, Naïve Bayes, and J48 Utilizing Bloom's Taxonomy-based Serious Game. *International Journal of Emerging Technologies in Learning (Online)*, *10*(2), 46.

Susi, T., Johannesson, M., & Backlund, P. (2007). Serious games: An overview.

Stemler, S. E. (2004). A comparison of consensus, consistency, and measurement approaches to estimating interrater reliability. *Practical Assessment, Research, and Evaluation*, *9*(1).

Teichmann, M., Ullrich, A., Knost, D., & Gronau, N. (2020). Serious games in learning factories: perpetuating knowledge in learning loops by game-based learning. *Procedia Manufacturing*, *45*, 259-264.

Ullah, M., Amin, S. U., Munsif, M., Yamin, M. M., Safaev, U., Khan, H., ... & Ullah, H. (2022). Serious games in science education: a systematic literature. *Virtual Reality & Intelligent Hardware*, *4*(3), 189-209.

Vicente-Serrano, S. M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J. J., López-Moreno, J. I., Azorin-Molina, C., ... & Sanchez-Lorenzo, A. (2012). Performance of drought indices for ecological, agricultural, and hydrological applications. *Earth Interactions*, *16*(10), 1-27.

Waeber, P. O., Melnykovych, M., Riegel, E., Chongong, L. V., Lloren, R., Raher, J., ... & Garcia, C. A. (2023). Fostering innovation, transition, and the reconstruction of forestry: critical thinking and transdisciplinarity in forest education with strategy games. *Forests*, *14*(8), 1646.

Weber, R. P. (1990). *Basic content analysis* (Vol. 49). Sage.

Weste, G. (2003) The dieback cycle in Victorian forests: a 30-year study of changes caused by Phytophthora cinnamomi in Victorian open forests, woodlands and heathlands. Aust. Plant Pathol. 32, 247–256.

Wong, Y. L., Bothma, T. J. D., & Smith, A. E. (2024). Effects of meaningful choices in serious games for meaningful learning.

Wollman, L. F. (2012). Research paradigms. *Retrieved from*. https://www.chds.us/coursefiles/research/lectures/research_paradigms/script.pdf

Wong, L. P. (2008). Data analysis in qualitative research: A brief guide to using NVivo. *Malaysian family physician: the official journal of the Academy of Family Physicians of Malaysia*, *3*(1), 14.

Wouters, P., van Nimwegen, C., van Oostendorp, H., & van der Spek, E. D. (2013). A meta-analysis of the cognitive and motivational effects of serious games. *Journal of Educational Psychology, 105*(2), 249–265. https://doi.org/10.1037/a0031311

Villarraga-Flórez, L. F., Rodríguez-Piñeros, S., & Martínez-Cortés, O. G. (2015). Social science in forestry curricula: A case study of Colombia forestry programs. *Sustainability*, *8*(1), 36.

Vogel, J. J., Vogel, D. S., Cannon-Bowers, J., Bowers, C. A., Muse, K., & Wright, M. (2006). Computer gaming and interactive simulations for learning: A meta-analysis. *Journal of educational computing research*, *34*(3), 229-243.

Yusoffa, A., & Shafirilb, S. (2019). The development of "forest ranger" as a 2D serious game application to increase awareness against illegal logging. *Development*, *6*(2).

Zentmyer, G.A. and Mircetich, S.M. (1966) Saprophytism and persistence in soil by Phytophthora cinnamomi. Phytopathology, 56, 7

Zhao, X., Lynch, J. G., Jr., & Chen, Q. (2010). Reconsidering Baron and Kenny: Myths and truths about mediation analysis. *Journal of Consumer Research, 37*(2), 197–206. https://doi.org/10.1086/651257

Zhonggen, Y. (2019). A meta-analysis of use of serious games in education over a decade. *International Journal of Computer Games Technology*, *2019*(1), 4797032.

Annex A:

Related Literature on the Use of SG in Forestry. The studies are arranged from the most recent publications

Author (Year)	Game Title; Location of the Case Study	Types of Serious Games; Key Issues in Forestry Addressed in the Game	Aim(s) of the Game; Theory Used in the Study	Game Features Evaluated to Determine the Players' Learning; Number of Participants; Quantitative Analysis Performed	Game Component(s) that Enhance Learning	Game Component(s) that Hinder Learning
Bolijn et al. (2022)	Benni's Forest; Indonesia	Digital simulation game: Reforestation	Increase awareness on the multiple challenges faced by reforestation projects; Did not use any theories	The score screen of the playthrough served as the basis to ask the players about their session; 21 participants; Descriptive statistics presented in a pie chart	**Web-based:** The game is web-based making it easily accessible for the participants. **3D Environment:** the 3D nature of the game made players feel that they are managing a real reforestation project. Such real-world visualisation enhances the conveying of how reforestation projects can make an impact.	**Game mechanics**: such as "forest prosperity preventing illegal logging" and "grass growing back on abandoned parcels" did not function properly as a tool to convince biodiversity and fertility. **Lack of game explanation:** The lack of clarity and explanation about the game aspects also limited the learning acquisition.
Menconi et al. (2025)	ES-Hunt; Perugia, Italy	Digital board game; Urban Forestry	Aims to raise awareness among young people about the diversity of urban trees and technical concepts such as	Did not mention the specific game feature that was evaluated to determine learning; 135 participants aged 10-14; Paired T-Test	**Specific game element:** Players successfully learned key concepts such as the diversity and variability of ecosystem services provided by urban trees. Specific details such as the municipal tree	Balancing engagement with the effectiveness of knowledge delivery was reportedly a challenge.

			species diversity, age diversity and ecosystem provisions; Mentioned several theories that are used in game-based educational instructions but unclear about how the theory was used in the game developed in their study.		cadastres (detailed registry of trees) enabled the facilitation of learning of key concepts, highlighting the roles of real-life data embedded in the game. **Flexibility**: this characterisation allows players to explore the game at their own pace, allowing different modes of learning and game preferences.	The competitive nature of the game encouraged the players to prioritise speed instead of the educational content.
Bengston et al. (2021)	IMPACT: Forestry Edition; No specific location was used in the game	Analogue card game; Forestry Future	The game enables forestry professionals and stakeholders creatively and holistically envision forest futures; Did not use any theories.	The specific game feature being assessed in the game is not mentioned, rather, the follow-up questions were about the holistic experience of the card game; Graduate and undergraduate students but the total number was not specified; Interview was used to assess the perception of the players	**Domain interactions:** The game enables players to systematically envision the future of forestry through the interactions of domains. The cascading impacts of changes can also be deduced through the game. Overall, the paper recommends social scientists to analyse the game results repeatedly to unearth socio-ecological systems in the game since the evaluation performed is rather in a surface level.	The rules were complex and intimidating requesting the developers ample time to get familiarised in the game mechanics. Improvements of the game include players writing their own impact cards or collaborate with other players.

Yusoffa & Shafiril (2019)	Forest Ranger Application; No specific place was integrated into the game but the illegal logging issues were contextualised in Malaysia	Digital 2D game; Illegal Logging	The 2D application intends to inform the public about illegal logging activities; used theories such as behaviourism, constructivism and social learning to shape the outcome of the instructional materials.	No evaluation was performed in the game, hence, the lack of specific game features assessed to identify learning efficacy; the total number of participants were not reported but the paper mentioned that it was a multidisciplinary group of players; the paper did not reach the evaluation stage as of the time of writing.	**Age-appropriate interface:** Despite the game itself not being evaluated, the proponents plan to modify the interface suitable for elementary and middle school students using child-friendly controls and interfaces.	The game followed the ADDIE Model (Analysis, Design, Development, Implementation and Evaluation). However, this model does not fully embrace game design principles which is an important aspect of learning.
Waeber et al (2023)	MineSet; Congo Basin as the Case Study	Digital role-play game; Deforestation	The game aims to facilitate engaging experiences and immerse into the complex issues of deforestation. The game offers the students a deeper understanding of the social dimensions that influence deforestation and their drivers; did not use any theories but	The game was assessed holistically and no specific game feature is evaluated post-game; 6 students tried to play the game; the evaluation was mostly a debriefing lasted for 4 to 6 hours a day.	The students regarded the game as a faster means to learn as compared to conventional lectures. **Simulations:** The simulations embedded in the game provided problem-solving skills among players with the game's illustrative nature increasing the interactions and encourages solution-finding to address the problems.	The detective narrative and problem-solving gameplay were found to be distracting for some players to fully grasp the entire scientific content. Having too much mystery in the game diluted the attention to the detailed biological processes involved. The numerous routes of strategies each player can take created an open-ended solution space. This poses challenges in assessing the true impact of educational effectiveness.

			mentioned the roles of games in bridging theory and practice for students to navigate complex issues.		The physical haptic tabletop game increases the exchanges among players and incites emotional engagements. The inclusion of stakeholder roles answered the obstacles of bringing experts in a classroom setting, thereby, enables students to learn how stakeholder engagements can address deforestation.	

Annex B:

Related Literature on the Use of SG in Tree Health

Author (Year)	Game Title; Location of the Case Study	Type of Serious Game; Key Issue in Plant and or Tree Health Addressed in the Game	Aim(s) of the Game; Theory used in the Study	Game Feature Evaluated to Determine the Players' Learning; Number of Participants; Quantitative Analysis Performed	Game Component(s) that Enhanced Learning	Game Component(s) that Hindred Learning
Maharaj (2015)	Gamification for Tree Health;	Digital 2D Game; Tree Health	This paper discussed three prototypes of gamified solutions for tree health. The competition has	No specific game feature that was evaluated or detailed in this paper; Three prototypes were produced from the competition	Save a Tree is centred on protecting trees by taking down enemies with axes attempting to cut down trees.	A less violent approach is recommended to improve the game Save a Tree. The second game could make sure of more diverse set of trees, pests and insects to

			produced three entries; Did not use any theories.	"Gamification for Tree Health"; No specific analysis was performed and detailed in the research.	Protect the Plant has a catchy musical theme embedded in the game with features effective for children in terms of teaching plant health. Tree Diversity Simulator, on the one hand, enables players to purchase and plant trees. Ecological components such as disease, economic transactions between players and other characters are some of the planned features to be added in the game.	explain the needs of plants, particularly when pests attack them. The game design is complex with implementation remains unfinished at the time of the writing of the paper.
Batson & Coleman (2008)	Calendon; No specific location was embedded that inspired the game.	Digital 3D board game; Tree Diseases and Pest	The game targets to increase awareness on the importance of forestry and tree health particularly among young adults; Did not mention any theories embedded in the game.	There is no clear indication that the CALENDON evaluation has been performed in any of the literature available on the web.	The "financial" component of the game invites players to explore options in order to better understand the importance of forestry and agriculture. This concept reinforces the students to tackle strategies that can result to successful forestry programs.	No points for improvement have been discussed in the article.

Annex C:

Related Literature on the Use of SG in Pest Management

Author (Year)	Game Title; Location of the Case Study	Type of Serious Game; Key Issue in Pest Management Addressed in the Game	Aim(s) of the Game; Theory Used in the Study	Game Feature Evaluated to Determine the Players' Learning; Number of Participants; Quantitative Analysis Performed	Game Component(s) that Enhanced Learning	Game Component(s) that Hindred Learning
Cosme & Turchen, (2020)	Insect World; No location was used as a reference for the game development.	Analogue Card Game with Role Playing Game interactions; Domains such as insect taxonomy, physiology, morphology and behaviour; Did not mention any theories in the game.	The game contains 288 cards which explores taxonomy, physiology, morphology and the behaviour of insects.	Learning was assessed by comparing the players correct answers from closed and multiple-choice questions, and card interaction index by capturing the strategies of the players via photographic recording; 92 undergraduate students; Direct observation and by audio recording to assess the general student behaviour towards the game.	The easy game dynamics were empirically observed to be a significant component that resulted to positive feedback towards understanding the game manual and design. The RPG design offered flexibility in decision making and problem solving while engagements was triggered by the card's contents, the manual, and the easy game play in general. The narrative and information from each card and manual	Players advised the changing of format from analogue to digital which is much preferred generally by users. Such ease of access through digitalised format are also viewed as a enriching game-based learning activity to reach a broader public response. The amount of required initial information to play the game was reported to be a main drawback. Additionally, the interpretation of game rules is also

					facilitated the linkage between the insect and another card. A key finding from the research highlighted that players were able to create strategies based on the information provided in the game without the overreliance on pre-knowledge about insects.	
de la Vega et al. (2022)	Spotted-Stop-It; There is no specific location that the game was contextualised to.	Digital 2D Mobile game; IPM	The game targets to incite the interests and participation as well as disseminate knowledge of the management of pests. The game was specifically inspired by the soft-skin fruit pest spotted wing Drosophila (Dropohila suzukii); Did not use any theory in the study.	Children aged 5-10 years old tested the game; a questionnaire was used to assess the game with results detailed in percentages	Through image association, participants were able to identify the spotted wing Dropohila. The management practices integrated in the game enabled participants to identify practices such as the harvest frequency, sanitation and alternative hosts during the gameplay.	The paper did not specifically discuss any limitations that have hindered the learning of the participants. However, the developers created a Spanish version to address the language barrier increasing the accessibility of the game.
Helmberger et al. (2022)	Pest Quest; Similar to earlier studies,	The game has two versions, analogue,	Pest Quest aims to increase the knowledge of the	33 respondents completed all the three assessments introduced in the	The students' perception regarding their learning was not heavily quantified in the study,	The interface built in Tabletopia was found to be difficult to use and consumes a large amount of internet connections. These two

	there is no specific location that was embedded in the game.	and digital card game formats; IPM	players in three domains, namely IPM terminologies, philosophies and decision-making; Did not use any theory in the study.	experimental set-up; Friedman tests and post hoc Nemenyi multiple comparisons were used to evaluate the scores from the 4-8 statements allotted under each domains.	however, the time span of gameplay could account for the lack of significant differences between the second pre- and post-assessment	factors need to be overcome before players can fully understand and strategically navigate the game.

Annex D:

Summary of Earlier Systematic Reviews on SG Features that Fosters and Hinders Learning

	Facilitates Learning		Hinders Learning	
Authors (Year): Key discussions	Authors (Year) being Cited	Game Features that Enhanced Learning	Authors (Year) being Cited	Digital Features that Hindered Learning
Dernat et al. (2025): Performed a systematic review on SG contextualised in agricultural issues, assessing how likely SGs are addressed to sustainability problems.	Plass et al. (2015)	**Altering Perspectives:** creates environments that are immersive, thereby, facilitating knowledge acquisition and application.	Not applicable	The paper did not discuss any game components that do not incite learning among the players.
Miao et al. (2022); Explored the gamification elements that improve learning as well as the prevailing theories adopted in gamification-led pro-environmental research.	Miao et al. (2022)	**Reward:** Most used learning tool in gamification followed by feedback, competition, points, goal, leaderboards, challenge, meaning and badges among others.	Not Applicable	The paper mentioned that only one out of the 56 articles compared has reported insignificant effects of gamification in pro-environmental behaviour but this was not discussed heavily nor specifically cited in the paper.

	Radziszweski et al. (2021); Cwil & Barnik, (2018); Nor & Azhar, 2017); Helmefalk & Rosenlund, (2020) Huber & Hilty (2015); Castelletti et al. (2018); Bardhan et al. (2015)	**Rewards:** enhances user engagement and fosters behaviour. Items like points, leaderboards and badges were mostly associated with rewards. **Meaning:** provides specific actions that may create persuasive systems. For instance, "persuade" meant to change the behaviour towards environmental protection.		
Ebrahim et al. (2015): highlighted the main advantages of mobile learning and the challenges it presents through mobile applications. It is worth mentioning that while this review heavily focused on mobile learning, the included studies may provide valuable insights to the current research since both tackles learning through digital environments.	Ebrahim et al. (2015) Goodison (2001)	Six functions were highlighted as the main benefits of mobile learning, namely "1)enhancing and building knowledge in any context; 2) allowing the collection of data specific to the present time and location; 3) acting as a path for learners to comprehend their unique paths of interest; 4) providing support by integrating work activities; 5) complementing other learning by supporting other learning tools and 6) integrating particular experiences as a part of a larger sum" (Ebrahim et al., 2015) **Mobile Device as the Means of Access:** This enhances the motivation of students through group discussions and mobile dialogues while receiving quick and efficient	Ebrahim et al. (2015) Maniar, et al. (2007) Dieterle et al. (2007)	**Informality**: this factor can lose some of the valuable educational gains due to mobile learning's 'more casual' in nature, particularly if access becomes too widespread. **Screen size:** Found to be limiting with at least 58 mm (2.28 in) as the screen size to better facilitate learning. **Virtual environment:** is discussed to be a limiting factor for real-life human interactions.

		feedback. The feedback mechanism also improves memory retention. Increasing motivation is linked more to learning that the actual completion of tasks.		
	Ruta (2009)	**Opportunity to apply to different contexts**: learning is proposed to be complementary with mobility beyond just providing information. Features like sharing photos, audio, and captions can enhance communication among actors enabling customisation and genuine learning experience.		
	Alhazmi & Rahman (2012)	**Addressing Pedagogical Issues**: Discussed to having both direct and indirect impacts particularly how the system can enhance the teaching and learning process of the students. Both the technological perspective and pedagogical elements has to be integrated to better combine technology and education support.		

Ravyse et al. (2017); revealed five central themes crucial in making SGs that required "intertwinning with pedagogical content to ensure succesful learning". The study presented compelling evidences on the roles of digital games that have direct impacts on cognition, behaviour or motor skills. Results demonstrated that learning mostly aligns with knowledge transfer followed by soft skills acquisition, and behavioural change.	Ke (2008); Ke & Abras (2013) Kiili (2005) Hwang et al. (2012) Bellotti et al (2012); Chent et al. (2014); Couceoro et al. (2013) Knight et al. (2010)	**Sensory stimuli:** increases the players' engagement with the learning material. The authors recommended that learning has to be embedded with an appealing storyline. To illustrate this, the "game's narrative should only be allowed to progress if the player displays the correct behaviour within the game" (Ravyse et al., 2017). **Linking the Game's reward to the Learning Outcome:** this increases the likelihood of accomplishing the intended impact of the game. **Learning style**: Students who played games that are suited to their own learning style were proven to have better learning results. Games should allow players to choose their own progression version to adapt to the players' own learning style. **Storyline:** this factor must be linked closely with the content instead of simply creating attractive presentation. The context should match the narrative for the learning material. **End User Collaboration in the design and play testing phases:** apart from learning engagements, games that	Hwang et al. (2012) Ke (2008) Ke & Abras (2013); Papastergiou (2009); Virvou & Katsionis (2008) Ravyse et al. (2017) Gonza´lez-Gonza´lez & Blanco-Izquierdo (2012); Kiili (2005); Van der Spek et al. (2013); Hong et al.	**Exclusively open-ended or linear game**: This dimension lowers the learning effectiveness of the game because of the alienated target audience. **Exogenous fantasy:** is found to be less effective in facilitating learning when compared to storylines embedded in the learning material. **Overly rich presentation**: a number of researchers claimed that overrepresenting rich information in the game can distract the students from the learning tasks. **Time-limits:** since SGs are highly embedded with constructivist theory, implementing time limits is counter-intuitive to explore learning. Due to the competition against clock, players may find it difficult to satisfy both learning and playing. Moreover, inciting competition against other players is often discouraged especially if the learning aspect remains the focus of the research. **Complex interfaces:** Game developers are advised to avoid complex interfaces because it would require a lot from novice players to become accustomed to the game and may induce cognitive load. Game interfaces should have straightforward dynamics.

		used user-collaborative design strategies successfully received positive feedbacks in terms of satisfaction	(2013); Hwang et al. (2015) Zin & Yue (2013)	**Mechanic control:** Games with hard-to-control mechanics such as the back-and-forth use of mouse and keyboards contributes to students' loss of interest.
	Ravyse et al. (2017); Hong et al. (2013)	**In-game abstraction:** Due to the fact that not every component in the game can accurately represent real-life scenarios, "implementing abstraction requires expert understanding of the content" (Hong et al., 2013). Additionally, pedagogical experts can ensure the proper integration of teaching and learning approaches into the game.	Ravyse et al. (2017)	**Competition:** this factor can raise anxiety among players making them quit the game or avoid the learning aspects of the game. However, competition can also incite interests and motivate players. To address this confounding effects, solutions include disabling competitive elements like player scores and leaderboards, and correlate these elements with other possible learning styles.
	Baranowski et al. (2011); Byun & Loh (2015); Dickey (2011)	**3D models and realistic sound:** these two factors are proven to help students experience the physical space. However, keeping with the visuals may be challenging because understanding the digital environment depends on the players' profile. For instance, 2D games for school children are unsophisticated while games designed for high schools are more realistically looking and more complex.		
	Gee (2005); Gonza´lez-Gonza´lez & Blanco-Izquierdo (2012)	**Avatar customisation:** When players are given the freedom to create avatars that they see themselves in, they are likely to engage with the game, thus increases motivation in learning the materials. When the budget is constrained, players having the freedom to choose from a range of prepared characters can be an option.		

	Johnson & Mayer (2010); Van Eck (2006)	**Non-Player Characters (NPCs)**: Players prefer interacting with NPCs through voice rather than text. Additionally, students are more accustomed to learning from facial expression and intonation of their teachers, hence, NPCs provide an alternative that also supports information and environment.		
	Admiraal et al. (2014); Ha¨ma¨la¨inen (2011); Kiili (2005; Schmitz et al. 2015)	**Collaborative learning through time pressure**: Time, in general, can be considered as a worthy opponent for players to win the game and channel collaborative learning.		
	Ha¨ma¨la¨inen (2011); Hwang et al. (2013); Ke and Abras (2013); Van Eck (2006)	**Scaffolding as an approach to learning**: this promotes a gradual introduction of levels, difficulty, and other practice levels that can help players acclimatise to the game's interfaces.		
	Ravyse et al. (2017)	**Player-to-Player interaction**: identified as a leading game success factor. Players tend to share tactics and solutions with one another even if collaboration is not an intended part of the game design.		
		In-game feedback and instant updates: The two game designs can provide immediate cause and effect		

	Cheng and Annetta (2012); Johnson & Mayer (2010); Cheng et al. (2015); Kiili (2005); Kuk et al. (2012)	scheme of the players' actions and showcase competitive standing, respectively. Instant updates align with several studies on recommending game rewards (e.g. points, leaderboards, level indicators) and resource tools (e.g. maps for resources) to avoid wasting time in the game.		
	Crookall (2014)	**Progress tracking as a debriefing tool**: this tool is vital for players to process the in-game activities and learning events. This can be in the form of generated progress-tacking reports or recollection of memorable learning activities embedded in the game.		

Anex E:

Recruitment Notice Post

Charl Justine Darapisa • You
Student - Digital Agriculture, Landscape Architecture, Rural Develop...
2mo • Edited •

Beneath the forest floor and across rural landscapes, a silent invader is on the move. Phytophthora cinnamomi—a deadly plant pathogen—is spreading, disrupting ecosystems, and challenging farmers, foresters, and conservationists alike.

🌿 CALL FOR RESEARCH PARTICIPANTS 🌿
Are you a Bachelor's, Master's, or PhD student passionate about integrated pest management, agroforestry, or gaming?

I'm inviting you to participate in a research study exploring "Silent Spread: A Phytophthora cinnamomi-Inspired Digital Serious Game" — a unique digital board game designed to teach players about the mechanisms behind plant disease spread and sustainable management practices. Silent spread is part of my Master's thesis, which is a requirement for the International Master's of Science in Rural Development degree at Ghent University Global Campus Universidad de Córdoba Humboldt-Universität zu Berlin

🎮 Participation is fully online
🕐 Takes only 45 minutes to 1 hour
📚 Help advance research in environmental education and game-based learning!

🔗 Register here: https://lnkd.in/eNdSz3Wx

📧 Any questions? Reach out at: charjustinedarapisa@gmail.com

Let's gamify learning and make plant pathology fun and impactful! 🌱 🕹️

April Mae Dalangin and 10 others · 2 comments • 1 repost

Like · Comment · Repost · Send

Annex F:

Structured Questionnaire: Silent Spread Questionnaire

Annex G:

Summary of guiding question to assist participants during the Cognitive Compass making session

Section 1 Reflection: Knowledge Acquisition as the Foundation

1. What key **knowledge or insights** did you gain from playing the game about *Phytophthora cinnamomi* and its management?

2. In a quick glance, can you think of **environmental, social, and economic issues**, **concepts, application** that the game addresses?

   Note: I will be writing their response and explore further. See Section 2 for a more in-depth question.

Sample expected results: Environmental (biodiversity loss, tree health, forest resilience, Dehesa); **Economic** (economic loss from tree mortality, loss of income, cost of maintenance and infestation containment); **Social** (collective effort to stop the pathogen, raising awareness and improving environmental education; rural development)

Section 2 Application: Application to the Three Pillars of Sustainability

Note: I will be reminding the participants about Bloom's taxonomy (remember, understand, apply, analyze, evaluate). In this way, they can be aware that I am now assessing the knowledge they learned in terms of applicability)

Environmental sustainability:

1. Did the game help you understand any **environmental challenges** related to forest or the Dehesa ecosystems? If so, which ones?

2. How do you think can the learning you acquired help you in the future to tackle these environmental challenges?

3. Which among the trivia, quizzes, in-game management and game challenges help you in realizing the application of the knowledge to these environmental challenges, issues, sustainable practices?

Economic sustainability:

1. Did the game help you understand any **economic aspects, and concepts** related to tree diseases or forest management? If so, which ones?

2. Can you think of sustainable practices—like those shown in the game—might help reduce economic losses or create long-term value? How?

3. Which among the trivia, quizzes, in-game management and game challenges help you in realizing the application of the knowledge to these economic consequences, opportunities or concepts? Can you elaborate please?

Social sustainability:

1. Did the game make you think any **tackling forest health are** related to communities or people's lives? If so, which ones?
2. What kind of social dimensions (eg. Collective action, social responsibility) did you acquire while playing the game?
3. Which among the trivia, quizzes, in-game management and game challenges help you in realizing the application of the knowledge to social dimensions or sustainability? Can you elaborate please?

Sample expected results: Sample statement chatgpt-generated: *"Seeing how much income people might lose because of tree death made me think of the ripple effect on communities. It's not just about the environment but about families and livelihoods. I liked how the game made me think about forest management as a long-term investment—not just a cost."*

Section 3: Gaps

1. After playing the game, do you think you would act or think differently about pathogens, tree health, and their connections to sustainability? Can you elaborate please?
2. Is there anything you wish the game had explored more deeply to learn more about P.cinnamomi and its applications in real life settings?

Annex H:

Link to the first version of the game: [Silent Spread First Version]

Annex I:

Summary of in-game quizzes and the players responses

Level	Quiz	Cognitive Process	Learning Content	Number of Times Explored	Answered Correctly	Answered Incorrectly
1	Which factor contributes to progressive tree decline?	Remembering	General Information	4	3	1
	Why are dehesas still vulnerable to decline despite their resilience?	Understanding	General Information	8	8	0
	What distinguishes the rapid decline pattern in infected trees?	Understanding	General Information	6	5	1
	What are Dehesas traditionally used for?	Remembering	General Information	8	8	0
	In which decade was *P. cinnamomi* isolated in Iberia?	Remembering	General Information	6	3	3
	Name two oak species affected by *P.cinnamomi*	Remembering	General Information	7	4	3
2	A dehesa farmer is facing increasing tree mortality due to *Phytophthora cinnamomi*. Which of the following actions would best help maintain livestock grazing capacity?	Applying	Spread mechanisms	5	5	0
	A local environmental agency wants to reduce chemical use in infected dehesas. Based on the text, what is the most practical next step?	Applying	Management Practices	6	4	2
	Given the threat of *Phytophthora cinnamomi* to tree cover in dehesas, how could farmers adapt their livestock management to minimize economic losses?	Applying	Management Practices	6	5	1
	A rural development planner wants to maintain economic sustainability in a region affected by *Phytophthora cinnamomi*. Which action would	Applying	Management Practices	6	6	0

	best help sustain extensive livestock farming in the dehesa?					
	If a dehesa ecosystem experiences a significant decline in holm oak health due to *Phytophthora cinnamomi,* how would this most likely impact the production of acorn-fed Iberian ham?	Analysing	Spread mechanisms	**7**	**6**	**1**
3	Based on the demonstration of how the area was infected by *P.cinnamomi*, which of the following best describes the factor that inhibits their transmission?	Analysing	Spread mechanisms	**10**	**2**	**8**
	Which management strategy would be most effective in slowing *Phytophthora cinnamomi* spread in a forested recreational area, considering feasibility and impact?	Evaluating	Management Practices	**4**	**3**	**1**
	Which condition would most compromise the effectiveness of *Phytophthora* management strategies that rely solely on soil treatments?	Analysing	Spread mechanisms	**3**	**3**	**0**
	Given a scenario where surface water from a nearby infested stream is used in irrigation, what is the best evaluation of the disease spread risk?	Evaluating	Spread mechanisms	**3**	**3**	**0**
	In evaluating disease management on a mixed-use farm, which activity would pose the greatest risk of long-distance pathogen spread?	Evaluating	Spread mechanisms	**2**	**2**	**0**
	Which of the following human activities requires stricter control in both agricultural and wild settings to limit *Phytophthora* spread?	Applying	Spread mechanisms	**8**	**8**	**0**
	If infections are spreading uphill, what should a land manager implement?	Evaluating	Management Practices	**2**	**2**	**0**

	If only one can be controlled, which has the higher impact?	Evaluating	Management Practices	**2**	**2**	**0**
	A farm shows rapid disease spread only in downhill areas. What factors are likely responsible?	Analysing	Spread mechanisms	**2**	**2**	**0**

ANNEX J:

Standardised Email used to Address Personal Bias

Silent Spread_Gameplay Schedule Inbox ×

C

Sat, Jul 19, 3:04 PM

Thank you very much for volunteering to participate in my data-gathering in connection with Silent Spread, a digital board game about Phytophthora cinnamomi.

You may access the game instructions at the following link:
1. Canva Public View
2. Google Drive

About the schedule you shared with me, would you be available on **Wednesday, July 23, at 4:00 PM?**

While the game is available for single and multiple players, it would be more fun and interesting if you had at least one colleague who could join us in the meeting. If none, I would be happy to give you a walkthrough of the game.

Thank you and looking forward to hearing from you.

Sincerely,

One attachment • Scanned by Gmail

ANNEX K:

Use of GenAI tools in the master's dissertation

☐ No use of GenAI tools

☒ One or more GenAI tools used

Indicate and describe, in case of using one or more GenAI tools, how you have used them:

	GenAI tool used as	**Description**	**Used tool(s)**
☐	Idea generator	Did not use AI for this task.	
☒	Search engine	Searching for literature that can support the arguments in the research, particularly in the Discussion section.	ChatGPT 5.0
☒	Writing assistant	Improving overall readability, simple grammar check, and asking for other academic styles of writing	ChatGPT 5.0
☒	Designer	Generating characters, visual, and audio support for the game	Canva Pro
☒	Practice tool	Explaining the necessary steps in performing PLS-SEM, asking for the adviseable thresholds, and cross-referencing whether explanations of the results are valid and logical	ChatGPT 5.0
☒	Data analysis	Cross-referencing whether explanations of the results are valid and logical	ChatGPT 5.0
☐	Efficiency booster	Did not use AI for this task.	
☐	Used in another way	Did not use AI for this task.	

ANNEX L:

Summary of Outer Loadings

Item	Analysing	Applying	Evaluating	Game Events	General information	In-game management	Management practices	Quiz	Remembering	Spread Mechanism	Trivia	Understanding
A3_AnalyseInterconnectedness	0.933											
AN2_IdentifySpreadPattern		0.946								0.975		
AN2_IdentifySpreadPattern							**0.605**					
AP1_ApplyAndIdentifyActions		0.768										
AP2_KnowledgeForStrategicDec...		0.868					0.843					
AP3_Unable to apply learning		0.852					0.823					
EV1_EvaluateManagementStrat...							0.923					
EV2_AssessDecisionImpacts							0.797					
EV2_AssessDecisionImpacts							**0.478**					
EV3_ConfidentinChoosingMan...							**0.695**					
EV3_ConfidentinChoosingMan...		0.852										
GE1_ChallengesHelpEvaluate				0.926								
GE2_HelpContentBetter				**0.204**								
GE3_ChallengesFun				**0.119**								
IM1_MakeMeaningfulDecisions						0.942						
IM3_GameTasksEasy						0.774						
QZ1_HelpfulQuizzes								**0.028**				
QZ2_Encouraging to think crit.								0.858				
QZ3_NonRepetitive								0.816				
RE1_RecallPcinnamomi									0.908			
RE1_RecallPcinnamomi									0.876			
RE2_RememberSymptoms									0.787			

RE2_RememberSymptoms												
RE3_EasyFactsRemembering									0.779			
TR1_RememberImportantFacts					**0.397**						1.000	
TR1_RememberImportantFacts												
TR2_Informative												0.784
UN1_DescribePathogenEffects												0.886
UN2_ExplainTreeMonitoringImportance												
UN2_ExplainTreeMonitoringImportance												0.882
UN3_UnderstandTheProcess										**0.665**		

ANNEX M:

Summary of Construct Reliability and Validity

Construct	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Analysing	**0.868**	**0.875**	**0.938**	**0.883**
Applying	**0.775**	**0.787**	**0.869**	**0.690**
Evaluating	**0.737**	**0.786**	**0.882**	**0.788**
Remembering	**0.750**	**0.773**	**0.857**	**0.669**
Understanding	**0.721**	**0.721**	**0.878**	**0.782**

ANNEX N:

Summary of Discriminant Validity – HTMT

	Analysing	Applying	Evaluating	Remembering	Understanding
Analysing					
Applying	**0.761**				
Evaluating	**0.783**	**0.718**			
Remembering	**0.098**	**0.243**	**0.346**		
Understanding	**0.165**	**0.228**	**0.642**	0.894	