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ORIGINAL

An Interactive Role-Playing Game to Promote Conceptual Understanding and Manage Cognitive Load in Plant Growth Systems

Un juego de rol interactivo para promover la comprensión conceptual y gestionar la carga cognitiva en los sistemas de crecimiento vegetal

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ABSTRACT

Digital role-playing games (DRPGs) hold strong potential for enhancing motivation and conceptual understanding in science education, yet their application in biology particularly plant growth and development remains underexplored, especially in relation to cognitive load management. The objective of the study are evaluate the vadility and practicality of media Bio-Garden Space, thus examine effect to students' conceptual understanding and cognitive load. The research employed the Multimedia-Based Instructional Design model developed by Lee and Owens, which consisted of analysis, design, development, implementation, and evaluation stages. The evaluation was carried out through a quasi-experimental method, with validation involving experts in content, media, and practitioners, and effectiveness testing conducted by comparing an experimental group using the DRPG and a control group with conventional instruction. The results indicated that *Bio-Garden Space* was categorized as "very valid" in terms of content, design, and visual presentation, and "very practical" in small-group implementation. Students who learned with the DRPG achieved significantly higher learning outcomes compared to the control group. Furthermore, the experimental group experienced significantly lower mental effort and extraneous cognitive load, while intrinsic cognitive load remained comparable across groups. These findings suggested that the integration of interactive real-time plant growth simulations and dynamic decision-making tasks enhanced students' conceptual understanding and enabled more efficient allocation of cognitive resources by reducing unnecessary processing. It was concluded that *Bio-Garden Space* is a valid, practical, and effective digital learning medium for teaching plant growth and development, providing strong pedagogical value and implications for broader implementation in science education.

Keywords: Digital Role-Playing Game; Plant Growth and Development; Cognitive Load; Learning Achievement; Game-Based Learning.

RESUMEN

Los juegos de rol digitales (DRPG) tienen un gran potencial para mejorar la motivación y la comprensión conceptual en la educación científica. Sin embargo, su aplicación en biología, en particular en el crecimiento y desarrollo de las plantas, sigue siendo poco explorada, especialmente en relación con la gestión de la carga cognitiva. El objetivo del estudio es evaluar la validez y la viabilidad de los medios de Bio-Garden Space, examinando así su efecto en la comprensión conceptual y la carga cognitiva de los estudiantes. La investigación empleó el modelo de Diseño Instruccional Basado en Multimedia desarrollado por Lee y Owens, que constó de etapas de análisis, diseño, desarrollo, implementación y evaluación. La evaluación se llevó a cabo mediante un método cuasiexperimental, con validación con expertos en contenido, medios y prácticas, y pruebas de efectividad realizadas comparando un grupo experimental que utilizó el DRPG y un grupo de control con instrucción convencional. Los resultados indicaron que Bio-Garden Space se categorizó como "muy válido" en términos de contenido, diseño y presentación visual, y "muy práctico" en la implementación en grupos pequeños. Los estudiantes que aprendieron con el DRPG lograron resultados de aprendizaje significativamente superiores en comparación con el grupo de control. Además, el grupo experimental experimentó un esfuerzo mental y una carga cognitiva externa significativamente menores, mientras que la carga cognitiva intrínseca se mantuvo comparable entre los grupos. Estos hallazgos sugieren que la integración de simulaciones interactivas del crecimiento de plantas en tiempo real y tareas dinámicas de toma de decisiones mejoró la comprensión conceptual de los estudiantes y permitió una asignación más eficiente de los recursos cognitivos al reducir el procesamiento innecesario. Se concluyó que Bio-Garden Space es un medio de aprendizaje digital válido, práctico y eficaz para la enseñanza del crecimiento y desarrollo de las plantas, con un gran valor pedagógico e implicaciones para una aplicación más amplia en la educación científica.

Palabras clave: Juego de Rol Digital; Crecimiento y Desarrollo de Plantas; Carga Cognitiva; Rendimiento Académico; Aprendizaje Basado en Juegos.

INTRODUCTION

Advancements in technology have profoundly reshaped educational practices, particularly through the increasing digitalisation of instructional media.[1] Among the innovations in this domain, game-based learning has gained prominence, with digital role-playing games (DRPGs) emerging as a rapidly expanding pedagogical approach.[2] DRPGs combine role-playing simulations with educational content to create interactive and immersive experiences that allow learners to adopt roles within scenarios that mirror real-world contexts.[3,4] One of the primary strengths of DRPGs is their flexibility, as they are not restricted by time or location,[5] and this approach design corresponds closely with the preferences of contemporary learners who are accustomed to technology-mediated environments.[3]

Extensive research has highlighted the pedagogical potential of DRPGs. Empirical studies suggest that these games can increase learner motivation,[6,7] cultivate critical thinking,[3,7] and promote collaborative learning.[8] Through role-playing, students are encouraged to solve problems,[9,10] make decisions,[11,12] and interact socially within digital environments.[13] In science education, such interactive learning opportunities can facilitate deeper exploration of concepts while sustaining learner engagement throughout the instructional process.[14,15] Furthermore, well-designed games have been shown to elicit both cognitive and emotional responses that contribute to meaningful learning outcomes.[16,17]

Despite these advantages, the integration of games into formal education still faces challenges. A central issue is the absence of well-established pedagogical frameworks to guide the effective implementation of games in classroom practice.[18] Without appropriate design, games may inadvertently result in negative consequences, such as distraction or cognitive overload.[19] This concern is particularly salient in science education, where students are required to engage with abstract and complex phenomena that can easily overwhelm working memory if not scaffolded properly. Technical barriers in implementing digital games in secondary education further compound these challenges.[20,21] Consequently, it is crucial to design educational games that are not only engaging but also pedagogically robust, with deliberate consideration of cognitive load. In this regard, understanding the role of cognitive load in learning is essential, as it fundamentally influences students' ability to process information and develop conceptual understanding.[22]

Cognitive load refers to the mental effort required to process and retain information within working memory.[23] When instructional materials are overly complex or insufficiently structured, excessive cognitive load may occur, thereby obstructing learning and inhibiting the development of meaningful knowledge.[22] This issue is particularly urge in science education, where learners frequently encounter abstract processes and dynamic systems that are inherently difficult to conceptualise. Educational games designed with cognitive load theory in mind offer a promising solution, as they can balance complexity with engagement.[24] By integrating interactive visualisations, providing scaffolding for tasks, and delivering immediate feedback, such games can reduce extraneous cognitive load while fostering germane load, ultimately supporting deeper conceptual understanding.[22,25]

Although numerous studies have highlighted the benefits of digital role-playing games in fostering motivation,[20,21] collaboration, and critical thinking skills,[3] limited attention has been given to their application in biology education, particularly in the context of plant growth and development. Existing studies incorporate real-time visualisations of plant growth that require students to make adaptive decisions, such as managing water, fertilization, or pest control.[1,26] Moreover, prior study has largely concentrated on affective outcomes, with relatively few attention given to evaluating the validity, practicality, and cognitive implication of DRPGs. The limited focus on cognitive load management is particularly concerning, as poorly designed games may diminish students' capacity to achieve meaningful conceptual understanding.

The present study introduces an interactive role-playing game that simulates plant growth processes in real time. The game not only presents biological concepts in a dynamic and visual format but also aims to strengthen conceptual understanding, critical thinking, and decision-making skills grounded in biological data.[27] Players assume the role of a farmer responsible for crop management from seed to harvest, making decisions such as watering, fertilisation, growth regulator application, and pest or disease management—each of which directly influences plant development. By embedding cognitive load principles into its design, the game seeks to balance challenge and comprehension, thereby maintaining student engagement without inducing overload.[22]

This study also contributes to the broader discourse on game-based learning by systematically examining the validity, practicality, and educational impact of DRPGs in biology instruction. By jointly addressing conceptual understanding and cognitive load alongside motivational and collaborative dimensions, the study provides a more holistic evaluation of DRPGs as instructional media. The outcomes are expected to inform pedagogical practices and support educators in implementing digital games that not only capture students' interest but also enhance mastery of scientific concepts while facilitating effective cognitive processing.To evalute the effectiveness of the media developed, the objective of the study are threefold: To evaluate the interactive digital role-playong game classified into a valid and practical category as a learning media according to the validators.

1. To examine examine the effect of interactive digital role-playing games in enhancing students' conceptual understanding.
2. To examine the effect of interactive digital role-playing games in reducing the cognitive load.

Thus, based on the above discussion, the following hypotheses were developed are:
H1: interactive digital role-playing games enhance students' conceptual understanding.
H2: interactive digital role-playing games minimalize lower cognitive load.

METHOD

This study employed a quasi-experimental research design complemented by the Multimedia-Based Instructional Design model.[28] This The model was selected because, in the development stage, it provides specific procedures for creating web-based multimedia, making it more appropriate than general instructional design models such as ADDIE. The model consists of five structured stages: (1) Analysis (needs assessment and front-end analysis), (2) Design, (3) Development, (4) Implementation, and (5) Evaluation. In this study, the evaluation stage was carried out through a quasi-experimental research method.

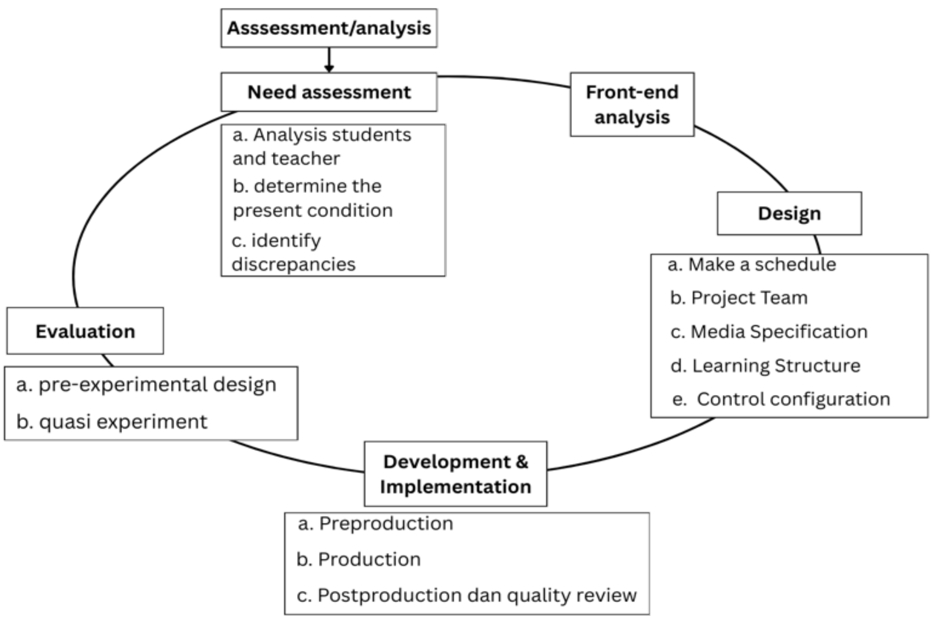

Figure 1. Research and Development Procedure Model

In this research, the evaluation phase was designed to examine two primary outcomes: students' conceptual understanding ("knowledge") and students' cognitive load (CL). Conceptual understanding was assessed through the significance of students' cognitive learning outcomes, while *cognitive load* was measured using a cognitive load questionnaire. These dual outcomes were evaluated to provide a more comprehensive picture of both the efficiency of information processing and the effectiveness of learning achieved through the game-based intervention. Figure 1 illustrates the development procedure of the *Gardening Game* according to the Lee[28].

Analysis Phase

The analysis phase of this study encompassed three key stages. To begin with, the profiles of the participants—comprising both learners and instructors—were examined to explore their characteristics, instructional needs, and potential barriers within the learning process. Next, the prevailing state of the educational environment was investigated through structured observations and interviews, yielding a detailed account of the instructional strategies, learning resources, and pedagogical approaches in current use. Lastly, disparities between the existing conditions and the targeted ideal scenario were identified, providing a basis for defining the strategic direction of instructional media development to maximize its relevance and pedagogical effectiveness.

Design Phase

The design phase of this study was carried out through five key steps: developing a project schedule, forming the project team, determining media specifications, designing the learning structure, and configuring control settings. The research activities were conducted from October 2024 to February 2025. The project team consisted of a designer, a developer, and a content creator. The media specifications were defined as an .exe format application, designed to be installed on the Windows operating system. The learning structure was aligned with the curriculum content on the plant growth system for Grade XI science major students under the Merdeka curiculum. The control configuration detailed the operational controls of the media and the design of each element, presented in the form of a comprehensive storyboard.

Development and Implementation Phase

The development phase in this study comprised three main sub-stages: preproduction, production, and postproduction. In the preproduction stage, a flowchart was created to map the sequence of the media development process, following the principles of multimedia computer-based learning. The production stage began with the design of the user interface, followed by the creation of 3D modeling assets, including in-game characters, environmental elements, and other supporting assets. The game was then developed using Unity game engine, with coding implemented to regulate each planting procedure within the gameplay. In the postproduction and quality review stage, a series of validation tests were conducted. These included content expert validation, media validation, and validation by biology education practitioners. The validation process followed established criteria adapted from Borg[29] and Lee[28], focusing on aspects of content accuracy, curriculum alignment, clarity of language, visual presentation, user interface, and ease of use. Each expert completed a structured validation sheet using a 5-point Likert scale (1 = very invalid to 5 = very valid). Validation results were analyzed by calculating mean scores and categorizing them into levels: very invalid (1,00–1,99), invalid (2,00–2,99), less valid (3,00–3,99), valid (4,00–4,49), and very valid (4,50–5,00). The product was considered feasible if it achieved at least the "valid" category (≥4,00). Suggestions from validators were incorporated into the revised version of the game before its implementation in the classroom trial.to ensure the feasibility and quality of the media prior to implementation.

Evaluation Phase

The evaluation phase in this study was based on four levels: reaction, knowledge, performance, and impact; however, the implementation focused only on Level 1 (reaction) and Level 2 (knowledge). Level 1 evaluation was conducted through concurrent validity using a pre-experimental design in a small group trial involving 10 Grade XI science-major students, aimed at assessing the practicality of the developed media. Subsequently, Level 2 evaluation was carried out through construct validity using a quasi-experimental design, comparing an experimental class with a control class to measure the effectiveness of the media in reducing students' cognitive load.

Participants

The participants in this study were divided into two main groups. In the pre-experimental design stage, 10 Grade XI science-track students with low, medium, and high cognitive levels were involved for the initial trial of the instructional media. In the quasi-experimental stage, 32 Grade XI science-track students were assigned to the control class and another 32 to the experimental class, with both groups having undergone an equivalence test to ensure homogeneity of prior abilities. Participant selection considered the representation of varying cognitive levels to ensure that the research findings reflected a range of student abilities. Recruitment was carried out in coordination with subject teachers to ensure that the participants' characteristics aligned with the research requirements. All participants took part in the learning activities in accordance with the research procedures and were provided with clear explanations regarding the study's objectives and the activities they would undertake. Furthermore, the researcher obtained ethical clearance and provided each participant with an informed consent form, ensuring that participation was voluntary and conducted in accordance with ethical research standards.

Research instruments

The research instruments used in this study consisted of instruments for the development study and the quasi-experimental study. In the development phase, the feasibility of the application-based media was assessed using validation sheets, practicality test sheets, and student response questionnaires. The media validation in this study was conducted using the Learning Object Review Instrument (LORI) developed by Nesbit[30] which serves as a standardized framework for evaluating the quality of multimedia learning objects. LORI includes nine key dimensions: content quality, learning goal alignment, feedback and adaptation, motivation, presentation design, interaction usability, accessibility, reusability, and standards compliance. The evaluation applied a convergent participation model, in which experts independently assessed the media and then discussed differing ratings to reach a consensus.[30] Two media experts and one instructional design expert participated in this process. Each dimension was rated using a 5-point Likert scale (1 = very poor to 5 = excellent), and the mean score determined the media validity level, with values ≥4,00 categorized as 'valid'. The inter-rater reliability yielded a Cronbach's alpha of 0,78, indicating high consistency. Additionally, a student response questionnaire consisting of eight items on ease of use and clarity of learning content was administered to gather user perceptions of the media's practicality and comprehensibility.; by subject matter experts to assess content feasibility, language quality, and presentation; and by instructional design experts to evaluate the learning design and its alignment with the curriculum.

Media Validation Criteria

Table 1. Items in LORI 1,5[30]

Item	Brief Description
Content quality	Veracity, accuracy, balanced presentation of ideas, and appropriate level of detail
Learning goal alignment	Alignment among learning goals, activities, assessments, and learner characteristics
Feedback and adaptation	Adaptive content or feedback driven by differential learner input or learner modeling
Motivation	Ability to motivate and interest an identified population of learners
Presentation design	Design of visual and auditory information for enhanced learning and efficient mental processing
Interaction usability	Ease of navigation, predictability of the user interface, and the quality of the interface help features
Accessibility	Design of controls and presentation formats to accommodate disabled and mobile learners
Reusability	Ability to use in varying learning contexts and with learners from different backgrounds
Standards compliance	Adherence to international standards and specifications

Meanwhile, student responses were measured using a questionnaire adapted from the EGameFlow scale developed.[31] This instrument was designed to assess students' enjoyment and engagement while interacting with educational games. It consists of eight dimensions: concentration, goal clarity, feedback, challenge, control, immersion, social interaction, and knowledge improvement. The adapted version used in this study contained 24 items (three per dimension), each rated on a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). The questionnaire was reviewed by two educational technology experts for content validity and pilot-tested with 32 students. The pilot test yielded a Cronbach's alpha coefficient of 0,89, indicating high internal consistency. This instrument provided a reliable measure of students' perceptions regarding the ease of use, motivational appeal, and learning effectiveness of the developed game-based media. In the quasi-experimental phase, students' cognitive load was assessed using the Cognitive Load Questionnaire

(CLQ) developed by Leppink et al.[32]. In this study, only the Extraneous Cognitive Load (ECL) dimension from the Cognitive Load Questionnaire was employed, as it directly reflects the cognitive effort imposed by the design and interface of instructional media. Since the primary objective was to evaluate the efficiency of the developed game-based media in reducing unnecessary cognitive processing, the Intrinsic and Germane Load dimensions were excluded. The adapted ECL scale consisted of four items rated on a 7-point Likert scale (1 = strongly disagree to 7 = strongly agree). The Cronbach's alpha coefficient obtained in the pilot test was 0,84, indicating good internal consistency.

Data analysis

The validity and practicality of the media were analyzed using a 5-point Likert scale, with percentage scores compared against the validation criteria, which consist of five categories: very invalid ($1 \leq X < 2$), invalid ($2 \leq X < 3$), less valid ($3 \leq X < 4$), valid ($4 \leq X < 5$), and very valid ($X = 5$). The test instruments were validated through content validity, construct validity, empirical validity, and reliability testing using Cronbach's Alpha. Data analysis for the quasi-experimental study began with an independent sample t-test to examine differences in pretest means. If both classes were equivalent, hypothesis testing was continued using an independent sample t-test between the control and experimental classes. All analyses were conducted using SPSS, with a significant t-test result interpreted as evidence of a treatment effect. Prior to the t-test and ANCOVA, assumption testing was performed, including normality testing (One-Sample Kolmogorov–Smirnov) and homogeneity testing (Levene's Test of Equality of Error Variances).

RESULTS

The analysis phase began with the distribution of questionnaires to teachers and students to identify learning needs, existing instructional conditions, and potential challenges in teaching the plant growth system topic. Data collected from three biology teachers revealed that classroom instruction remained predominantly lecture-centered, with minimal use of interactive or technology-enhanced media. Learning materials were generally limited to static presentations, which resulted in low student engagement and limited opportunities for inquiry or exploration. Teachers highlighted the necessity for an application-based interactive medium that is easy to operate, encourages student participation, and aligns with the learning objectives of the current curriculum. These findings emphasized the need to develop a game-based learning resource that could enhance conceptual understanding while reducing cognitive load during complex biological processes.

Meanwhile, questionnaire results from 32 students revealed that most experienced difficulties in understanding abstract concepts related to plant growth, particularly regarding internal and external factors influencing the process. A total of 78 % of students reported that learning would be more engaging if supported by interactive media that could dynamically visualize growth processes. Additionally, 65 % stated that their cognitive load increased when relying solely on static text and images from books or slides. These findings highlight the urgency of developing an interactive application-based learning medium to improve conceptual understanding and reduce cognitive load.

The design phase consisted of learning content design and media design. The learning content design was aligned with the plant growth system topic in the *Kurikulum Merdeka* for Grade XI science-track students and was adapted to their cognitive characteristics. The media design involved specifying the application format (.exe) compatible with the Windows operating system, developing a detailed storyboard, and configuring media controls for interactive navigation. The storyboard outlined the sequence of instructional content and game mechanics to ensure both scientific accuracy and logical gameplay flow. Visual elements, including 3D models of plant components, environmental settings, and supporting assets, were developed with attention to clarity, color balance, and realism to facilitate conceptual understanding while maintaining visual appeal. Control configurations were designed to ensure intuitive user interaction and accessibility across varying levels of digital literacy among students.

The outcome of the development and implementation stages is an interactive learning application called Bio-Garden Space, which features a farming simulation game with various seed options. The game incorporates fundamental theories on plant structure and growth processes. The gameplay begins with seed purchasing, followed by planting and seedling growth into mature plants. Throughout the growth process, players are required to perform watering, apply growth hormones, and select fertilizers appropriate to the plant's specific needs. In addition, the game simulates the occurrence of pests and diseases based on real biological conditions, prompting players to apply proper control strategies. Through its *role-play* model, students take on the point of view of a farmer, providing an experiential learning environment that closely mirrors real-life practice. This approach is designed to develop students' *muscle memory* in both understanding theoretical concepts and applying practical steps in crop cultivation. A detailed visualization of the game's flow and features is presented in figures 1.

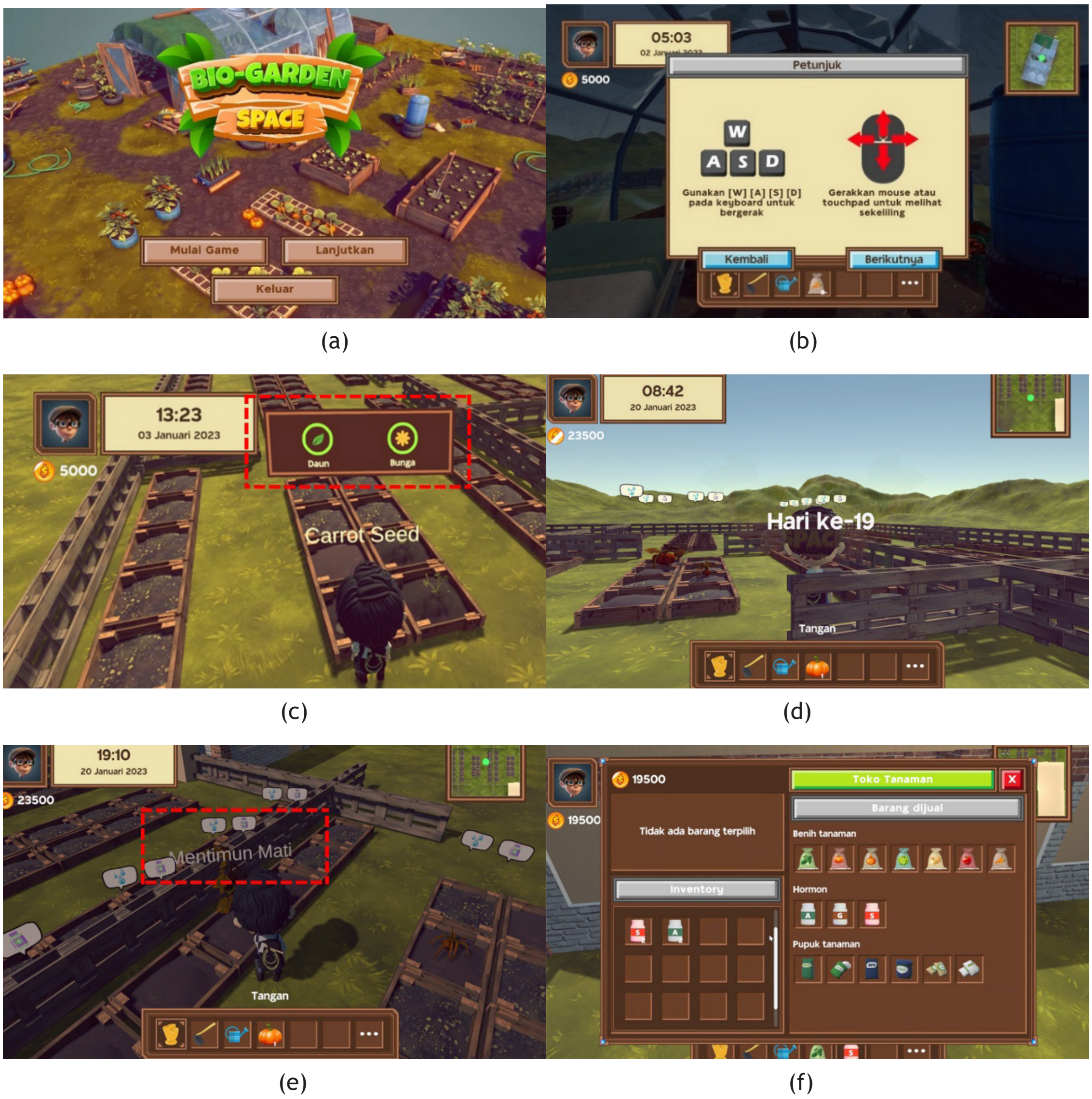

Figure 1. Game Display. (a) Opening game; (b) control panels; (c) Plants require water based on a specific watering Schedule; (d) Indicators of plant health, hormone needs, and fertilizer requirements, (e) Plant death notification; (f) Fertilizer, pesticide, and hormone storage

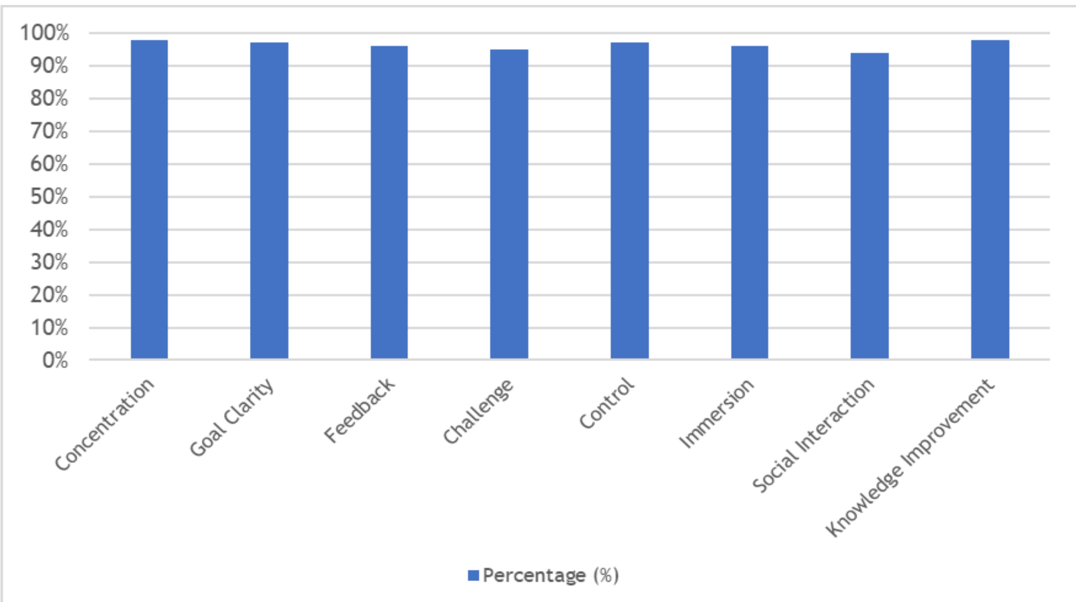

Figure 2. Result of Small-group Implementation

After the development stage was completed, a small-group implementation was conducted using a pre-experimental design involving 10 senior high school science-track students with high, medium, and low cognitive levels. In this phase, students were asked to complete an evaluation questionnaire adapted from the EGameFlow scale, which measures learners' enjoyment and engagement in game-based learning across eight dimensions: concentration, goal clarity, feedback, challenge, control, immersion, social interaction, and knowledge improvement. The questionnaire replaced the earlier simplified indicators of visual appearance, ease of understanding the content, and ease of media use to provide a more comprehensive and validated measure of the media's practicality and motivational appeal. The results of this assessment were used to obtain initial feedback on the feasibility and practicality of the media before conducting large-scale implementation trials. The detailed results are presented in figure 2.

After the development stage was completed, the evaluation phase was conducted, which in this study referred to four levels: Level 1 (reaction), Level 2 (knowledge), Level 3 (performance), and Level 4 (impact). The implementation focused on Level 1 and Level 2. At Level 1, face validity was carried out by media experts to assess the initial appearance and feasibility of the media, with the results presented in table 2. At Level 2, content and media validation were conducted by subject matter experts and practitioner validators using a validation sheet adapted from the Learning Object Review Instrument (LORI) developed by Nesbit, Belfer, and Leacock. In this study, these dimensions were contextualized to assess aspects of content accuracy and curriculum alignment, clarity and depth of the learning material, feedback and interactivity, motivational appeal, visual and interface design, usability, and technical accessibility. The results of the expert and practitioner validations, summarized in tables 3 and 4, indicated that the media met the "very valid" criteria across all dimensions, confirming its feasibility and quality for classroom implementation.

Table 2. Practitioner validation

Main Aspect	Sub-Aspect / Assessment Indicator	Percentage (%)	Description
Game Design and Content	Game design	100	Very valid
	Concept of learning content in the game	100	Very valid
	Relevance to learning objectives	100	Very valid
Instructional Relevance and Implementation	Relevance to curriculum	100	Very valid
	Feasibility in classroom use	100	Very valid
	Contribution to learning outcomes	100	Very valid
Media Display and Usability	Layout and navigation	93	Very valid
	Visual and aesthetic design	91	Very valid
	Ease of use (usability)	95	Very valid
Total average		97,6	Very valid

Table 3. Content validation

Main Aspect	Sub-Aspect / Assessment Indicator	Percentage (%)	Description
Content Feasibility	Scientific accuracy	100	Very valid
	Curriculum alignment	100	Very valid
	Depth of content	100	Very valid
Presentation Feasibility	Integration of concept and game context	100	Very valid
	Instructional clarity	100	Very valid
	Interactivity and responsiveness	100	Very valid
Language Feasibility	Clarity of language and information	100	Very valid
	Language clarity	100	Very valid
	Terminology appropriateness	100	Very valid
Total average		100	Very valid

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Table 4. Media Validation			
Main Aspect	**Sub-Aspect / Assessment Indicator**	**Percentage (%)**	**Description**
Game Design Quality	Visual and aesthetic design	100	Very valid
	Interface consistency	100	Very valid
	Animated character display	100	Very valid
	Character design quality	100	Very valid
	Expressiveness and visual appeal	100	Very valid
Ease of Use (Usability)	Layout and navigation	95	Very valid
	Interactivity and responsiveness	95	Very valid
	Understanding of game flow	100	Very valid
	Clarity of objectives	100	Very valid
	Familiarity of navigation	95	Very valid
Functionality and Performance	Loading time and system stability	100	Very valid
	Audio-visual synchronization	100	Very valid
	Accessibility across devices	95	Very valid
Total Average		98,9	Very valid

Subsequently, the evaluation at Level 2 (knowledge) was carried out through a construct validity test using a quasi-experimental design involving experimental and control classes to assess the effectiveness of the media. The effectiveness test aimed to determine whether the use of the developed media could improve students' learning achievement, as higher learning achievement reflects a better conceptual understanding of the subject matter. Prior to further testing, prerequisite analyses were performed, including normality and homogeneity tests. The results of the normality test are presented in table 5.

Table 5. Result of normality test			
Class	**Significance**		**Description**
	Pretest	**Posttest**	
Control	0,200	0,113	normally distributed data
Experiment	0,200	0,200	normally distributed data

Based on table 5, it can be stated that the pretest and posttest data of the students were normally distributed, with the significance values for each dataset being greater than 0,05 ($p > 0,05$). No data were found outside the normal range or as extreme values. Subsequently, a homogeneity test using Levene's Test was conducted, and the results are presented in table 6.

Table 6. Result of homogenity test			
Class	**Significance**		**Description**
	Pretest	**Posttest**	
Control	0,166	0,077	homogenous data variance
Experiment	0,167	0,077	homogenous data variance

Based on table 6, the pretest and posttest data were categorized as homogeneous, as indicated by significance values greater than 0,05 ($p > 0,05$). Therefore, the analysis was continued with a sample equivalence test using ANOVA on the pretest scores, the results of which are presented in table 7.

Table 7. Result of equivalence test		
Class	**Significance**	**Description**
	Pretest	
Control	0,83	no significant differences
Experiment	0,85	no significant differences

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Based on table 7, the pretest data indicated no significant differences, as evidenced by p-values greater than 0,05 ($p > 0,05$). Therefore, the control and experimental classes were considered equivalent and suitable for use as research samples. Subsequently, hypothesis testing was conducted to examine both conceptual understanding and the effect of the media on cognitive load, with the results presented in tables 8 and 9. Students' conceptual understanding was reflected through the significance of the pretest-posttest results and the influence of the media in reducing Extraneous Cognitive Load (ECL), demonstrating that effective media use can enhance learning achievement as well as conceptual comprehension.

Table 8. Descriptive data and ANCOVA of the post-test results

Class	N	Mean	S.D.	Adjusted mean	Std. error	F
Experiment	32	66,86	11,48	67,61	1,07	37,19*
Control	32	59,16	9,73	58,4	1,07	

Table 9. t-test result of the cognitive load dimensions on the post-questionnaire of the two groups

	Class	N	Mean	S.D.	t
Mental Load	Experiment	32	5,25	0,79	-0,58
	Control	32	5,36	0,81	
Mental Effort	Experiment	32	2,7	1,11	-2,85*
	Control	32	3,49	1,12	

Table 10. t-Test Results for the Extraneous Cognitive Load (ECL) Dimension on the Leppink Questionnaire

Dimension	Group	N	Mean	S.D.	t
ECL	Experimental group	32	4,11	0,78	−7,734*
	Control group	32	5,67	0,83	

Table 8 shows that the experimental class obtained a higher post-test mean score than the control class. The ANCOVA result ($F = 37,19$, $p < 0,05$) indicates a significant difference between the two groups, demonstrating that the use of the developed learning media had a significant effect on improving students' learning achievement. This improvement in learning achievement also reflects a deeper conceptual understanding of the material.

Across cognitive-load measures, the experimental condition demonstrated a clear advantage. On the Leppink Cognitive Load Questionnaire (table 10), the experimental group reported significantly lower Extraneous Cognitive Load (ECL) than the control group ($M = 4,11$, $SD = 0,78$ vs. $M = 5,67$, $SD = 0,83$; $t = -7,734$, $p < 0,001$; Hedges' $g = -1,91$), while Intrinsic Cognitive Load (ICL)—reflecting perceived task complexity—was comparable between groups (ns). Complementing this result, the Paas Mental Effort Scale analysis (table 9) showed that the experimental group expended significantly less cognitive effort ($p < 0,05$) to complete the same learning tasks.

Collectively, the findings presented in tables 8, 9, and 10 indicate that the developed instructional media contributed significantly to the enhancement of students' learning achievement while simultaneously reducing extraneous cognitive load. These results imply that the game-based learning environment promoted a more efficient cognitive processing mechanism, allowing learners to allocate their mental resources toward deeper comprehension and meaningful conceptual integration rather than being constrained by superfluous cognitive demands.

DISCUSSION

The development of the Bio-Garden Space game successfully addressed the instructional gaps identified during the analysis phase. Teachers reported that their current teaching practices remained predominantly teacher-centered, with limited interactively, while students experienced difficulties in understanding abstract concepts and reported high cognitive-load when relying on static text and image.[33,34] These findings reinforce prior research suggesting that complex biological processes such as plant growth require dynamic visualizations to foster meaningful learning.[27,35] The use of interactive digital role-playing games with three-dimensional visualizations creates a learning environment that transforms abstract processes into observable and manipulable phenomena.36 Such visual and experiential features in digital devices help students focus on essential biological relationships while reducing unnecessary cognitive demands.[37,38]

The design phase ensured that both content and media aspect aligned with the cognitive characteristics of Grade XI students and the requirements of the Kuirkulum Merdeka. The Bio-Garden Space game offered contextualized learning that mirrors real-life agricultural. Integrating interactive digital role-playing games with three dimensional visualizations establishes a learning context which abstract processes into tangible and interactive experiences. Such visual and experiential features help students focus on essential biological content while reducing unnecessary cognitive demands.[27,39] The use of 3D models and realistic visualizations further supported students' conceptual understanding by reducing abstraction practices.[40,41] Three-dimension models, intuitive navigation, and immersive virtual content as components that drive classroom learning because they allow learners to construct accurate mental models, engage in exploratory interactions, and experience contextualize problem solving.[42,43] The attention to user friendly navigation and accessibility addressed the variation of students' digital literacy levels in enhancing the practicality of the media for learning use.[44,45]

Validation results confirmed the quality and pedagogically feasibility of media. Expert and practitioner assessments rated the media as "very valid" category across all aspects, including game design, content accuracy, and visual presentation. The criterias of educational game is not only technically well designed, but also pedagogically sound.[46,47] In particular, the integration of accurate content and engaging design elements has been shown to enhance both learning outcomes and learner motivation in digital environment.[48] The content and media validation reached nearly perfect validity percentages, with only minor refinements suggested in terms of usability. These findings demonstrate that Bio-Garden Space meets expert standards of instructional quality, game mechanics, and visual appeal. The interactive features foster active learner engagement, scientifically accurate content that avoids misconceptions, and a user interface designated for intuitive and seamless interaction. The developing of high-quality 3D learning resources cultivating positive emotions among students and reducing cognitive load can enhance college students' learning resilience and mitigate academic risks.[49] The media promote active learner engagement by enabling students to explore, make decisions, and interact with accurate content in ways that align with Vygotsky's sociocultural theory, where knowledge is co-construtured through meaningful activity.[50,51] Scientifically accurate content minimizes misconceptions, allowing students concentrate on meaningful learning tasks.[52,53]

The quasi-experimental results demonstrated that students who learned with the Bio-Garden Space game achieved significantly higher conceptual understanding compared to the control group. The integration of real-time plant growth simulations and dynamic decision-making tasks provides richer opportunities for conceptual understanding.[54] The combination of real-time plant growth simulations and dynamic decision-making tasks created structured opportunities for students to thest hypotheses, observe consequences, and adjust strategies.[55] Role-play as farmers managing water, fertilization, and pest control required learners to connect biological principles with problem-solving decisions, which in turn activated critical thinking processes and sustained cognitive engagement.[20,21] The finding of this study extends the clear effect on students' learning achievement in biology. This media gains can be further explained by the cognitive mechanisms embedded in the game design, as the structured decision-making and problem-solving tasks not only foster conceptual understanding but also help manage students' mental effort and extraneous cognitive load.[56,57]

Equally important, the findings indicate that the media reduced students' extraneous cognitive load (ECL) and mental effort, while intrinsic load remained comparable between groups. Decision-making and problem-solving skills within a well-designed game play a direct role in reducing mental effort and extraneous cognitive load (ECL). Within the framework of Cognitive Load Theory,[22] game designs that incorporate structured challenges, clear rules, and immediate feedback help students focus on relevant information rather than on confusing or irrelevant elements. The decision-making mechanisms allow learners to practice selecting appropriate strategies based on content representation, while problem-solving activities stimulate cognitive engagement without imposing excessive working memory demands.[58] The DRPGs helped students to allocate cognitive resources more efficiently by reducing unnecessary processing.[59] When the game flow is intuitive such as through a simple interface, logical navigation, and dynamic visualizations. ECL is further reduced because students do not need to allocate cognitive resources to interpret technical instructions. Previous study show playing an immersive role-playing game significantly improved adult learners' understanding of higher-level mathematics, particularly basic differentiation, with the largest gains observed among participants with low to medium prior mathematical knowledge.[60] The The interactive visualization and immediate feedback embedded in the DRPG likely acted as scaffolds, guiding students' focus on essential aspects of plant growth and development.[61,62] The relevance of these findings to biology education is notable. Understanding plant growth and development requires grasping dynamic and interrelated processes that are often difficult to convey through static illustrations or lectures.[46,63]

The result demonstrate that the Bio-Garden Space is a valid, practical, and effective digital role-playing game that promotes conceptual understanding while managing cognitive load in plant growth systems. The DRPG provided a situated learning environment where students could experiment with biological variables and directly observe the consequences of their actions.[2] This not only improved conceptual understanding but also encouraged decision-making skills grounded in biological reasoning.[26,59] Compared to earlier research such as, which emphasized static visualizations, this study highlights the added value of real-time, interactive, and decision-based gameplay in supporting learning. The integration of DRPGs offers both theoretical and practical implications.[17,64] Theoretically, this study demonstrates that game-based learning can be pedagogically sound when evaluated not only in terms of motivation but also with respect to learning achievement and cognitive load. Practically, the media can serve as a pedagogically sound and technologically feasible resource for teaching complex biological topics in schools.[65] Future studies should examine its long-term impacts, explore the integration of collaborative elements within gameplay, and expand its application to toher biology domains to further strengthen its role in foresting deeper and sustainable learning outcomes.

CONCLUSIONS

The interactive digital role-playing game Bio-Garden Space was categorized as very valid in terms of practitioner, content, and media validation, and highly practical in small-group implementation. The quasi-experimental findings demonstrated that students who learned through Bio-Garden Space achieved significantly higher conceptual understanding and lower Extraneous Cognitive Load (ECL) compared to those taught conventionally, while their intrinsic cognitive load remained comparable, indicating that the complexity of the biological material was equivalent between groups. These results suggest that the integration of real-time plant growth simulations and decision-making tasks within the game facilitated more efficient cognitive processing by reducing extraneous load, enabling students to focus on meaningful learning. Overall, Bio-Garden Space is a valid, practical, and pedagogically effective digital learning medium that enhances students' conceptual understanding and cognitive efficiency in learning plant growth systems, offering a strong framework for future applications of digital role-playing games in science education.

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CONFLICT OF INTEREST
The authors declare that there is no conflict of interest.

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