



Student engagement and conceptual change through gamified flipped classrooms in biology education

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ABSTRACT

The gamified flipped classroom (GFC) is an extension of the traditional flipped classroom (FC) that embeds gamification elements into digital independent learning prior to face-to-face sessions. This study addresses the limited student engagement and persistent misconceptions commonly found in ecosystem learning by comparing students' cognitive engagement, conceptions, and conceptual change patterns when learning through FC and GFC. A quasi-experimental design was employed involving 70 tenth-grade students assigned to FC and GFC groups, with learning conducted over four meetings. Cognitive engagement was measured using the four-scale Student Course Cognitive Engagement Instrument (SCCEI) after the intervention, supported by semi-structured interviews and documentation of student learning notes. Students' conceptions were assessed using a four-tier multiple-choice test administered before and after learning, and conceptual change patterns were examined based on shifts in conception categories from pretest to posttest. The data were analyzed descriptively. The results indicate that students who learned through GFC demonstrated higher cognitive engagement across all indicators, developed more scientifically accurate conceptions, and exhibited more positive conceptual change patterns than those who learned through FC. GFC was particularly effective in reducing misconceptions, increasing sound understanding, and promoting construction-type conceptual changes. These findings suggest that integrating gamification into flipped classroom learning can enhance cognitive engagement and support deeper reconstruction of students' conception in biology education. It is recommended that GFC be considered as an alternative instructional strategy to improve concept mastery in ecosystem learning and to support more meaningful student engagement.

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INTRODUCTION

Misconceptions have long been recognized as a persistent challenge in science and biology education, as students often construct alternative conceptions that differ from scientifically accepted explanations and tend to be resistant to change (Achour et al., 2025; Treagust & Duit, 2008). In the context of ecosystem learning, previous studies consistently report that students experience substantial misconceptions related to energy flow, material cycles, and interactions among ecosystem components (Firman et al., 2020; Nurfadilah & Rochintaniawati, 2021; Nurhidayah et al., 2020; Triana, 2023). These misconceptions can stem from inappropriate delivery of the material, limited learning experiences, and conventional learning that provides insufficient opportunities for students to actively construct their own knowledge (Hanifah et al., 2022; Nurhidayah et al., 2020). Such conditions highlight the need for learning strategies capable of addressing these conceptual problems more effectively.

One important approach to overcoming this challenge is conceptual change-oriented learning. Conceptual change refers to the process by which learners' initial inaccurate or incomplete conceptions are transformed into coherent and scientifically accepted explanations (Chi, 2008; Heddy et al., 2018). This process is complex, involving knowledge restructuring, reflection on prior conceptions, and the integration of new information (Chi, 2013). Because of this, learning strategies that encourage deeper levels of cognitive engagement are essential for supporting the conceptual change process (Sinatra & Dole, 2013). A growing body of research has demonstrated that conceptual change-based instruction can effectively reduce misconceptions across various scientific topics (Uke et al., 2024; Vančugovienė et al., 2025).

The flipped classroom (FC) is one strategy that promotes active and self-directed learning. In this strategy, content delivery is shifted outside the classroom through videos or digital media, while in-class time is devoted to discussion, practice, and problem-solving (Hew et al., 2021). Several studies have reported that FC improves students' academic performance (Gayeta & Caballes, 2017; Moneke & Nwanneka, 2024; Nurjannah et al., 2023). However, students' cognitive engagement, particularly during the pre-class phase, remains a challenge, as many do not consistently demonstrate optimal effort in preparing for class (Huang et al., 2019). This indicates the need for instructional innovations capable of strengthening students' engagement before and during the learning process.

Cognitive engagement is defined as the mental effort students invest in understanding content and processing information (Fredricks et al., 2004). The ICAP framework proposed by Chi & Wylie (2014) categorizes engagement into passive, active, constructive, and interactive modes, with constructive and interactive activities being most effective in fostering deep learning and conceptual change. Therefore, learning strategies that encourage these higher forms of engagement are needed to support meaningful conceptual development.

One instructional innovation that has gained increasing attention is the integration of gamification into the flipped classroom strategy. Gamification involves integrating game elements (e.g., points, badges, challenges, and leaderboards) into non-game learning contexts to enhance motivation and engagement (Groening & Binnewies, 2019; Lo & Hew, 2020). Research has shown that gamification enhances intrinsic motivation, creates enjoyable learning experiences, and fosters higher levels of cognitive engagement (Baydas & Cicek, 2019; Zainuddin et al., 2019; Zhao et al., 2021). Moreover, empirical evidence indicates that GFC improves motivation, cognitive engagement, collaboration, satisfaction, learning efficiency, and conceptual understanding while simultaneously reducing misconceptions (Durrani et al., 2022; Majid et al., 2024; Ng & Lo, 2022; Yu & Yu, 2024). These findings suggest that GFC may help address the engagement limitations commonly found in FC, especially in pre-class learning.

Despite these promising results, research that directly compares FC and GFC, particularly in relation to students' cognitive engagement, conceptions, and patterns of conceptual change in ecosystem learning remains limited. Most existing studies have examined GFC in general instructional contexts, with less attention given to how gamification-enhanced flipped classroom supports conceptual change processes within specific biology topics. Addressing this gap, the present study aims to examine differences between FC and GFC in supporting students' cognitive engagement, conceptions, and conceptual change patterns during ecosystem learning. This study is novel in that it integrates cognitive engagement, students' conceptions, and conceptual change patterns within a single comparative framework focused on ecosystem learning. The findings are expected to contribute to the development of technology-enhanced biology education strategies that promote cognitively engaging learning

experiences and more meaningful conceptual development. Guided by this rationale, the study addresses the following research questions:

1. How does students' cognitive engagement in ecosystem learning compare between FC and GFC?
2. How do students' conceptions before and after ecosystem learning compare when the learning is implemented using FC and GFC?
3. How do the patterns of students' conceptual change in ecosystem learning compare when the learning is implemented using FC and GFC?

METHODS

Research Design

This study employed a quasi-experimental design with a non-equivalent pretest–post-test control group structure (Creswell & Creswell, 2018) compare students' cognitive engagement and conceptual change when learning through the Flipped Classroom (FC) and the Gamified Flipped Classroom (GFC). A pretest was administered to identify students' initial conceptions, while the post-test measured conceptual change and cognitive engagement because cognitive engagement was intended to capture students' overall response to the complete learning experience. Both groups had been familiarized with their respective instructional strategies through the previous topic for three sessions, ensuring that students were accustomed to the procedures and that the data collected were more valid and free from bias. All instructional activities were carried out by a certified biology teacher who regularly taught both classes to avoid external intervention, and the researcher was present only as a non-participatory observer.

Population and Samples

The population of the study consisted of tenth-grade students from a senior high school in Bandung, and a total of 70 students were selected as the sample through purposive sampling. The students were organized into two existing classes of 35 students each, which were designated as the control group (FC) and the experimental group (GFC), as shown in Table 1. All participants and their guardians provided informed consent prior to data collection to ensure voluntary participation and ethical compliance.

Table 1

Demographic Characteristics of the Participants

Demographic Variable	FC	GFC	Total
Grade level	Grade 10	Grade 10	Grade 10
Age range (years)	15-16	15-16	15-16
Male students	15	16	31
Female students	20	19	39
Prior experience with online learning	Yes (35)	Yes (35)	Yes (70)
Total participants	35	35	70

Instrument

Two primary instruments were used in this research. The first was a 20-item four-tier multiple-choice test designed to assess students' conceptions before and after instruction and to serve as the basis for analyzing conceptual change. Each item consisted of five answer options, five reasoning options, and two confidence levels (sure/not sure). The items were developed based on the revised Bloom's Taxonomy, covering cognitive levels from remembering (C1) to evaluating (C5). The test measured three core concepts in the ecosystem topic: ecosystem components (Concept 1), interactions among components (Concept 2), and factors affecting the ecosystems (Concept 3), all aligned with the national curriculum learning objectives. A set of 46 multiple-choice questions was given to 30 individuals, and each of the questions was analyzed for its reliability and validity. The overall reliability of the questions was excellent, obtaining a Cronbach's alpha of 0.96. Individual item correlation coefficients ranged from 0.195 to 0.753, demonstrating that there was validity evidence to support the interpretation of the scores for that item. From the analyses, seven of the items were deemed not to achieve a minimum threshold for item validity; thus, of the remaining 39 items, it was determined that 85% of the items were valid for use, with the remaining few requiring some revision. For the purposes of this study, each of the indicators was represented by 20 items that were selected based on the strongest psychometric evidence and consideration of validity, discrimination, and item difficulty.

The second instrument was a cognitive engagement questionnaire adapted from the Student Course Cognitive Engagement Instrument (SCCEI) developed by Barlow et al. (2020). It comprised 27 positively and negatively worded statements rated on a four-point Likert scale. The indicators included interactivity with peers, constructive note-taking, and active processing. All instruments were validated and piloted before implementation. Additional qualitative data were collected from students' learning notes and semi-structured interviews consisting of 14 questions. The interviews explored students' learning experiences, strategies used, perceptions of FC or GFC, and interactions during group discussions, and were also used to clarify responses to selected questionnaire items.

Procedure

The research procedure consisted of three stages: pre-research, implementation, and post-research. The pre-research stage included a series of activities such as conducting a literature review, developing and validating the research instruments, preparing learning content and media, obtaining research permissions, familiarizing both classes with their respective learning strategies, and designing the instructional materials to be used during the study.

The implementation stage began with the administration of the pretest, followed by four instructional meetings conducted over the course of one month. After completing the learning sessions, students took the post-test and filled out the cognitive engagement questionnaire. The procedure during this stage is illustrated in Figure 1, which outlines the sequence of activities for both the control and experimental groups. In the out-of-class phase, the control group studied the ecosystem topic independently using an e-module, while the experimental group accessed the material through the Nearpod platform, enriched with gamification features such as achievements, avatars, leaderboards, points, and quests. During the in-class phase, both groups took part in regular classroom learning following the discovery learning model as outlined by Widodo (2021). The post-research stage involved processing and analyzing the data, organizing and presenting the findings, drawing conclusions, and preparing the final manuscript.

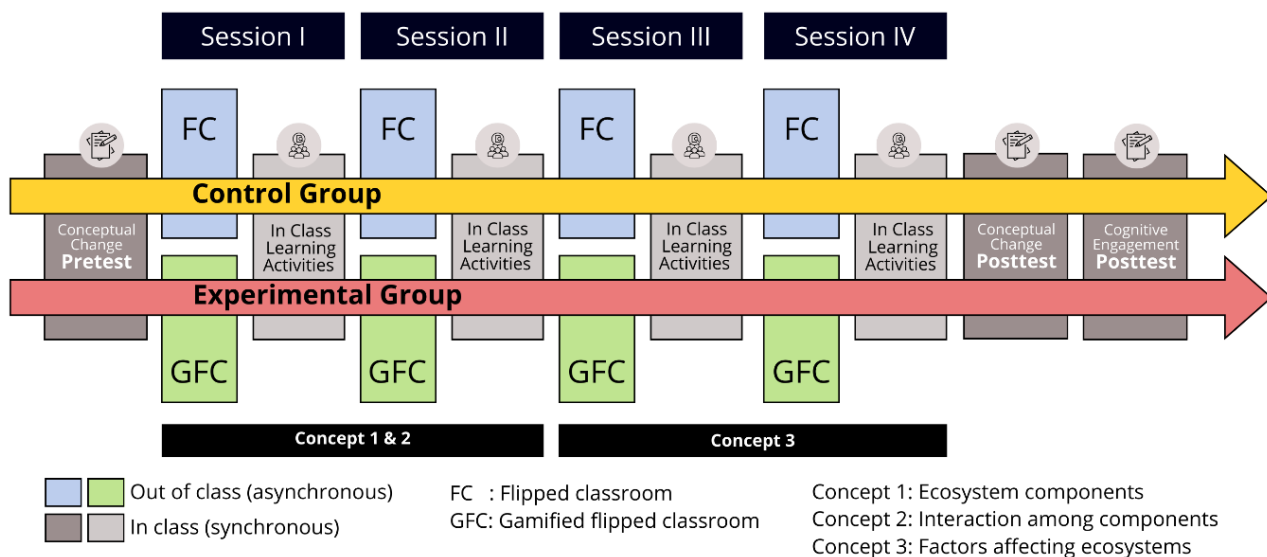


Figure 1. Research Design of FC and GFC Implementation in Ecosystem Learning

Data Analysis Techniques

Data were analyzed descriptively. Cognitive engagement scores were calculated based on the mean score of each indicator for both groups and presented in bar charts. Students' conceptions from the pretest and posttest were analyzed using a four-tier scoring scheme adapted from Samsudin et al. (2016) and Gani et al. (2023). The scoring assigned codes ranging from 0 to 5 represent sound understanding (SU), partial positive (PP), partial neutral (PNT), partial negative (PNg), misconception (MC), and no understanding (NU), as shown in Table 2. The proportion of students in each category was calculated for every item. Although the analysis also generated concept-based proportions for each of the three ecosystem concepts, the results reported in this article focus on the overall average representing students' understanding of the ecosystem topic as a whole to provide a clearer comparative picture between the two groups.




















Table 2
Categories of Students' Conceptions

Conceptions Category	Tier-1 (Answer)	Tier-2 (Confidence Level)	Tier-3 (Reason)	Tier-4 (Confidence Level)	Score
Sound understanding (SU)	True	Sure	True	Sure	5
Partial Positive (PP)	True	Sure	True	Not sure	4
	True	Not sure	True	Sure	
	True	Not sure	True	Not sure	
Partial Netral (PNt)	True	Sure	False	Sure	3
	True	Sure	False	Not sure	
	True	Not sure	False	Sure	
	True	Not sure	False	Not sure	
Partial Negative (PNg)	False	Sure	True	Sure	2
	False	Sure	True	Not sure	
	False	Not sure	True	Sure	
	False	Not sure	True	Not sure	
Misconception (MC)	False	Sure	False	Sure	1
No Understanding (NU)	False	Sure	False	Not sure	0
	False	Not sure	False	Sure	
	False	Not sure	False	Not sure	

(Gani et al., 2023; Samsudin et al., 2016)

Conceptual change was analyzed by examining the transition of each student's score from the pretest to the posttest for all item. These transitions were categorized into five conceptual change patterns: construction (Co), revision (R), complementation (Cp), static (S), and disorientation (D), based on Kristianti et al. (2019) and Diana et al. (2024), as presented in Table 3. Similar to the conception analysis, conceptual change percentages were calculated for each concept, but only the overall distribution is presented to maintain clarity and avoid excessive fragmentation of results. Data were presented in tables and visualized using a Sankey diagram, following the visualization model developed by Kristianti et al. (2019) and Diana et al. (2024).

Table 3
Patterns of Students' Conceptual Change

Conceptions Category		Conceptual Change Patterns	Interpretation	Conceptual Change Direction Symbols
Pretest	Posttest			
NU	PNt	Construction (Co)	Students are able to construct scientific understanding by transforming incorrect or absent prior knowledge into accurate scientific concepts	
NU	PP			
NU	SU			
MC	PNt			
MC	PP			
MC	SU			
PNg	PNt			
PNg	PP			
PNg	SU			
NU	MC	Revision (R)	Students are able to revise their conceptual understanding toward a more accurate direction, although they have not yet achieved a fully correct scientific understanding	
NU	PNg			
MC	PNg			
PNt	PP	Complementation (Cp)	Students are able to integrate new knowledge with their prior knowledge in a more coherent and comprehensive manner	
PNt	SU			
PP	SU			
SU	SU	Static (S)	No change occurs in students' conceptual understanding, either remaining correct or remaining incorrect	
PP	PP			
PNt	PNt			
PNg	PNg			
MC	MC			
NU	NU			
SU	PP	Disorientation (D)	Students experience a shift in conceptual understanding toward a less accurate or more erroneous conception than before	
SU	PNt			
SU	PNg			
SU	MC			
SU	NU			
PP	PNt			
PP	PNg			
PP	MC			
PP	NU			
PNt	PNg			
PNt	MC			
PNt	NU			
PNg	MC			
PNg	NU			
MC	NU			

(Diana et al., 2024; Kristianti et al., 2019)

RESULTS AND DISCUSSION

Comparison of Students' Cognitive Engagement in Ecosystems Learning Between FC and GFC

Cognitive engagement plays a critical role in learning success because it reflects how deeply students process information, draw on prior knowledge, and construct new understanding through interaction and learning activities (Chi & Wylie, 2014; Heddy et al., 2018). The overall analysis of cognitive engagement (Figure 2) indicates that students in the experimental group using the gamified flipped classroom (GFC) achieved a higher average engagement score (71.0) than those in the control group using the flipped classroom (FC) (65.8). This finding suggests that GFC was more effective in fostering deeper cognitive engagement. Higher levels of engagement create more favorable conditions for conceptual change, as engaged students are more likely to participate actively, think critically, and

meaningfully connect new information with existing knowledge structures (Gayeta & Caballes, 2017; Sinatra et al., 2015).

The advantage of GFC can be attributed to the integration of gamification elements that sustained students' motivation and attention throughout the learning process. These elements encouraged students to engage more actively with pre-class and in-class activities, reducing passive learning behaviors. Students in the experimental group reported that the video pop-up questions encouraged them not just to watch passively, but to think and actively process the material. In contrast, many students in the control group felt that the FC strategy became monotonous because it relied heavily on independent reading with minimal interactive features. This finding aligns with self-determination theory (Deci & Ryan, 2012), which emphasizes that learning engagement increases when students' needs for competence, autonomy, and relatedness are supported, conditions that gamification can help fulfill (Botte et al., 2020).

Analysis by indicator (Figure 3) further supports these findings. Both groups obtained their highest scores on the active processing indicator, indicating that FC and GFC similarly encouraged students to engage cognitively during learning activities. However, the experimental group demonstrated a higher level of interactivity with peers (73.7) than the control group (66.0), suggesting that GFC better supported collaborative learning. These interactions facilitated idea elaboration, concept clarification, and information exchange, all of which contribute to the development of deeper understanding (Barlow et al., 2020; Chi et al., 2018). The constructive notetaking indicator showed a score of 62.9 for the experimental group and 60.6 for the control group. Although the difference is relatively small, the result indicates that GFC still encouraged students to take more meaningful notes, processing information, linking it to existing knowledge, and producing original summaries or reflective responses rather than merely copying. Constructive notetaking accompanied by immediate feedback can enhance metacognitive awareness and help students correct misconceptions (Heddy et al., 2018).

The active processing indicator in the experimental group reached 76.3, compared with 70.9 in the control group. This suggests that GFC prompted students to engage more frequently and deeply with learning materials. Interactive and feedback-driven activities required students to respond immediately, monitor their understanding, and revise their thinking in real time. Consistent with previous research, embedding interactive questions within learning media has been shown to improve information retention and academic performance (Deng et al., 2024). Moreover, the competitive and collaborative atmosphere fostered by gamification enhances both cognitive and social engagement (Guerrero-Quíñonez et al., 2023; Torres-Martín et al., 2022), helping students maintain focus and persistence throughout the learning process (Zainuddin et al., 2019).

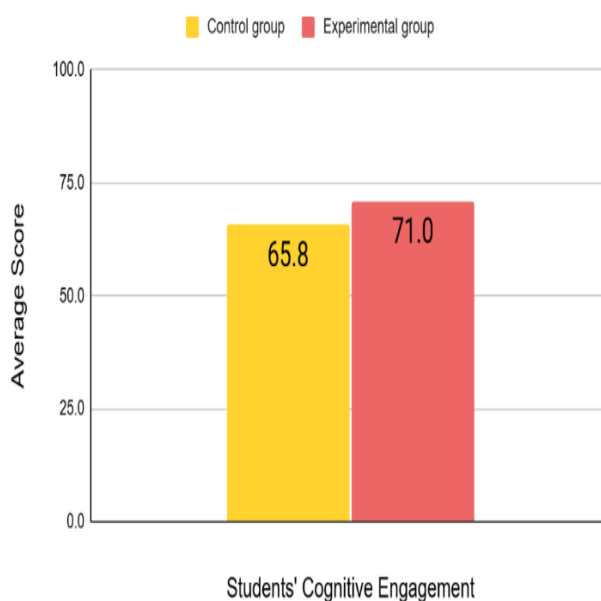


Figure 2. Overall Students' Cognitive Engagement in Control and Experimental Groups

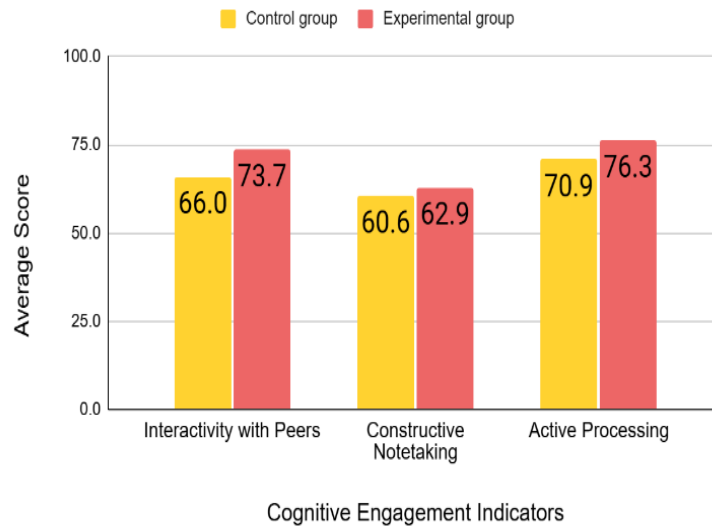


Figure 3. Students' Cognitive Engagement by Indicators in Control and Experimental Groups

Comparison of Students' Conceptions Before and After Ecosystem Learning Using FC and GFC

Students' conceptions of the ecosystem topic were examined through their pretest and posttest results. The pretest results (Figure 4) show that both groups started with relatively similar initial conditions, characterized by high proportions of NU and MC, while SU remained low. On average, students in the FC group fell into the NU category at 27.6% and MC at 19.0%, whereas students using GFC showed NU at 27.2% and MC at 16.6%. SU in both groups was still below 15%. These results indicate that most students entered the learning process with limited or inaccurate conceptions of ecosystem concepts. This finding is consistent with previous studies showing that high school students often struggle with misconceptions related to ecosystem interactions (Firman et al., 2020) and factors influencing ecological balance, particularly energy flow (Ulfa et al., 2024), largely due to conventional instruction that provides limited interaction and suboptimal use of learning media (Nurfadilah & Rochintaniawati, 2021; Triana, 2023). After the learning session, clear differences emerged between students learning through FC and those learning through GFC (Figure 4). Posttest results reveal that students using GFC experienced a much larger increase in the SU category, from 14.9% to 68.8%, whereas those learning with FC improved from 13.4% to 36.6%. Conversely, NU dropped sharply to only 0.9% among students using GFC, while students in the FC setting still remained at 8.2%. MC also decreased more substantially in the GFC strategy (from 16.6% to 8.4%) compared with FC (from 19.0% to 16.3%). A comparison of conceptual categories between pretest and posttest for both conditions is presented in Figure 4. Taken together, these results indicate that GFC was more effective than FC in improving students' conceptions, particularly in reducing misconceptions and strengthening scientifically accurate understanding. These findings are consistent with prior research showing that collaborative, technology-supported FC environments can gradually enhance student engagement and academic outcomes (Torres-Martín et al., 2022).

The superior outcomes observed in the experimental group can be linked to the role of gamification in enhancing attention, motivation, and cognitive focus (Groening & Binnewies, 2019). Gamified activities provided immediate feedback, allowing students to test their initial ideas and revise inaccurate conceptions during the learning process. Immediate feedback is critical for conceptual reconstruction, as it enables learners to identify inconsistencies in their thinking and adjust their understanding accordingly (Sailer & Sailer, 2021). This mechanism supports meaningful learning, where students actively build more accurate scientific understanding. In contrast, although FC promotes independent learning, the absence of interactive and motivational elements may limit students' willingness to critically examine and revise their misconceptions.

These results are further supported by previous findings showing that GFC tends to outperform traditional FC in terms of efficiency, clarity of instruction, and student motivation and satisfaction (Durrani et al., 2022). Other studies also note that integrating gamification into FC can create a more meaningful learning experience by combining synchronous and asynchronous activities that promote flexibility and active participation (Lopes et al., 2024). More broadly, meta-analytic evidence shows that

GFC consistently yields greater improvements in academic achievement, motivation, and student engagement compared to FC alone (Yu & Yu, 2024).

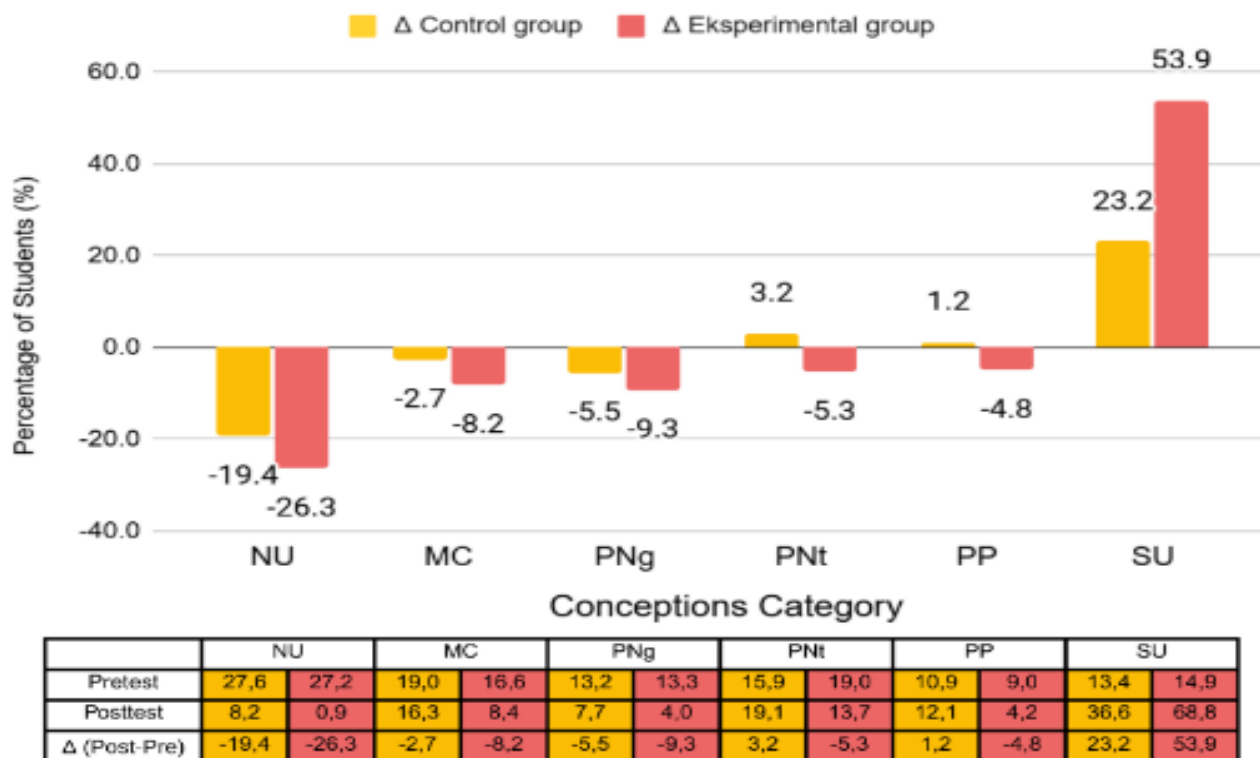


Figure 4. Comparison of Students' Conception Categories (Pretest-Posttest) between Control and Experimental Groups

Comparison of Students' Conceptual Change Patterns in Ecosystem Learning Using FC and GFC

Table 3 present the differences in the distribution of conceptual change patterns between the control and experimental groups. Overall, the experimental group showed a higher proportion of construction (46.1%) compared with the control group (36.2%), indicating that GFC more effectively supported the reconstruction of scientifically accurate concepts. The proportion of complementation was also higher in the experimental group (17.9%) than in the control group (10.1%), suggesting broader conceptual development. In contrast, disorientation was lower in the experimental group (7.6%) than in the control group (15.0%), implying that the conventional FC still carried a higher risk of shifts toward inaccurate conceptions. Figure 6 further illustrates that the dominant pathways in the experimental group were transitions from NU and MC to SU (16.1% and 10.3%), while the control group (Figure 5) only reached 8.4% and 4.9%, respectively.

The comparison of conceptual change patterns in the first concept, ecosystem components (Table 4), also showed consistent findings. The experimental group reached a higher proportion of construction (52.0%) than the control group (40.0%). Meanwhile, the control group still displayed a substantial proportion of static patterns (30.9%) and disorientation (9.7%), both higher than in the experimental group. The dominant pathways in the experimental group were NU to SU (18.3%) and MC to SU (16.6%). In contrast, the largest shift in the control group was SU to SU (static) at 10.3%. These results reinforce the view that misconceptions tend to be resistant to change, especially for concepts that require restructuring of existing conceptual frameworks (Agustina & Indana, 2021; Chi, 2008). One misconception found in this concept was the belief that producers generate oxygen through respiration, revealing that students still misunderstood basic metabolic processes in plants.

The patterns observed in the second concept, interactions among ecosystem components (Table 4), also reflected a stronger construction trend in the experimental group (36.2%) compared to the control group (31.4%). The control group again showed the highest proportion of static patterns (35.3%) and a higher disorientation rate (17.1%), while the experimental group recorded only 8.6%. The shift from NU to SU in the experimental group reached 10.5%, indicating greater restructuring of prior conceptions. A misconception detected in this concept involved the belief that *Cercospora* sp., which causes leaf spot in chili plants, performs predation on its host. This misunderstanding likely arose

because students equated tissue damage with predation. In reality, predation (including herbivory) results in rapid death of part or all of the prey organism, whereas parasitism involves a prolonged interaction in which the parasite harms but does not immediately kill its host, precisely the mechanism used by the fungus.

The conceptual change patterns for the third concept, factors affecting ecosystem balance (Table 4), also revealed clear differences between groups. The experimental group again showed a higher proportion of construction (50.0%) than the control group (37.1%). Disorientation remained high in the control group (18.2%), while the experimental group showed only 9.5%. The dominant pathway in the experimental group was NU to SU (19.5%), whereas in the control group, the largest pathway was MC to MC (static) at 6.4%. An example misconception in this concept was the belief that *Daphnia* sp. thrives better in low oxygen levels. This error was likely due to students' difficulty connecting information in the reading passage with the data table, resulting in an incorrect interpretation of the relationship between water quality parameters and organism abundance.

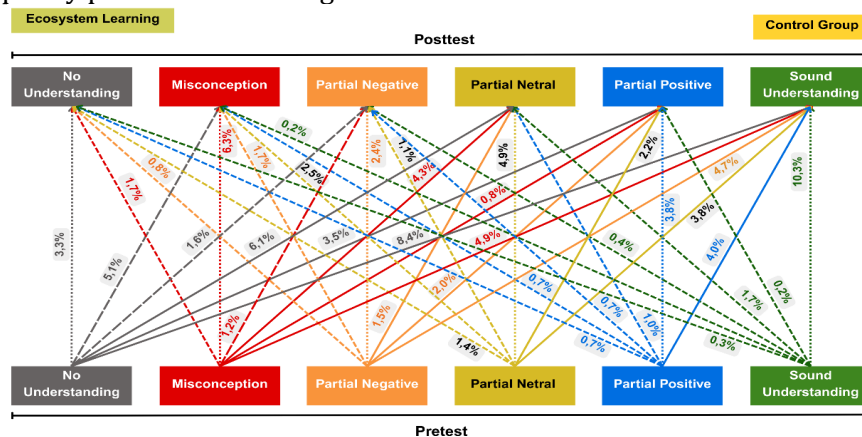


Figure 5. Proportion of Students' Conception Categories (Pretest-Posttest) in the Control Group

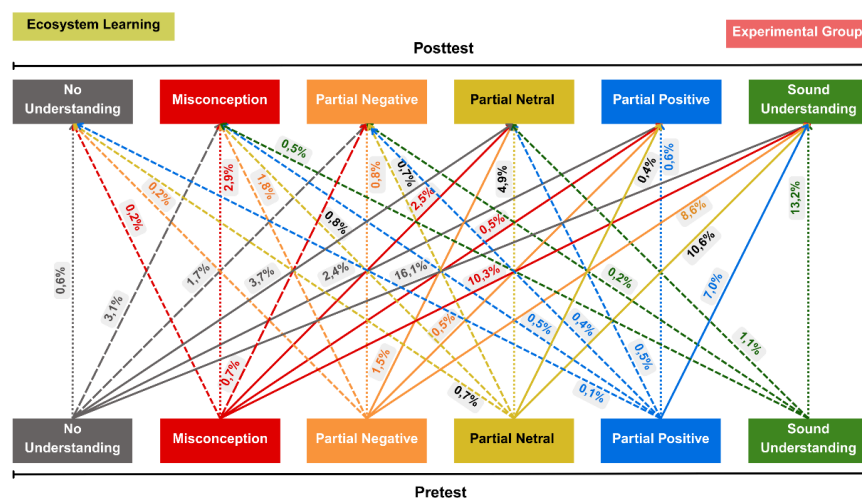


Figure 6. Proportion of Students' Conception Categories (Pretest-Posttest) in the Experimental Group

Table 4

Comparison of Students' Conceptual Change Patterns between Control and Experimental Groups

Patterns	Scheme	Percentage of Students (%)							
		Concept 1		Concept 2		Concept 3		Overall	
		C	E	C	E	C	E	C	E
Construction	NU → Pnt	8.6	2.3	3.8	4.8	6.0	4.0	6.1	3.7
	NU → PP	2.9	3.4	1.9	1.0	5.7	2.9	3.5	2.4
	NU → SU	9.7	18.3	7.6	10.5	7.9	19.5	8.4	16.1
	MC → Pnt	7.4	2.9	1.9	1.9	3.6	2.6	4.3	2.5
	MC → PP	1.1	1.1	0.0	0.0	1.2	0.5	0.8	0.5

Patterns	Scheme	Percentage of Students (%)							
		Concept 1		Concept 2		Concept 3		Overall	
		C	E	C	E	C	E	C	E
	MC → SU	4.6	16.6	5.7	4.8	4.5	9.5	4.9	10.3
	PNg → PNt	1.1	1.1	1.9	1.9	1.4	1.4	1.5	1.5
	PNg → PP	1.1	0.6	3.8	0.0	1.0	1.0	2.0	0.5
	PNg → SU	3.4	5.7	4.8	11.4	6.0	8.6	4.7	8.6
	Total	40.0	52.0	31.4	36.2	37.1	50.0	36.2	46.1
Revision	NU → MC	3.4	4.0	4.7	1.0	7.1	4.3	5.1	3.1
	NU → PNg	0.6	0.6	1.0	1.9	3.3	2.6	1.6	1.7
	MC → PNg	1.1	0.0	1.0	1.0	1.4	1.2	1.2	0.7
	Total	5.1	4.6	6.7	3.8	11.9	8.1	7.9	5.5
Complement- ation	PNt → PP	3.4	0.6	1.9	0.0	1.4	0.5	2.2	0.4
	PNt → SU	5.7	10.9	2.9	11.4	2.9	9.5	3.8	10.6
	PP → SU	5.2	7.4	4.7	10.5	2.1	3.1	4.0	7.0
	Total	14.3	18.8	9.5	21.9	6.4	13.1	10.1	17.9
Static	NU → NU	5.2	0.0	0.0	0.0	4.8	1.7	3.3	0.6
	MC → MC	8.6	2.3	3.8	2.9	6.4	3.6	6.3	2.9
	PNg → PNg	1.1	0.0	2.9	1.0	3.1	1.4	2.4	0.8
	PNt → PNt	3.4	5.7	5.7	4.8	5.5	4.3	4.9	4.9
	PP → PP	2.3	1.1	8.6	0.0	0.5	0.7	3.8	0.6
	SU → SU	10.3	10.9	14.3	21.0	6.2	7.6	10.3	13.2
	Total	30.9	20.0	35.3	29.5	26.4	19.3	30.9	22.9
Disorientation	MC → NU	0.6	0.0	2.9	0.0	1.7	0.7	1.7	0.2
	PNg → NU	1.1	0.6	1.0	0.0	0.2	0.0	0.8	0.2
	PNg → MC	1.1	0.6	1.0	1.9	2.9	2.9	1.7	1.8
	PNt → NU	1.1	0.0	1.0	1.0	2.1	1.0	1.4	0.7
	PNt → MC	1.7	1.1	1.9	0.0	4.0	1.2	2.5	0.8
	PNt → PNg	0.0	0.0	1.0	1.0	2.4	1.2	1.1	0.7
	PP → NU	0.0	0.0	1.0	0.0	1.0	0.2	0.7	0.1
	PP → MC	1.1	0.0	0.0	1.0	1.0	0.5	0.7	0.5
	PP → PNg	0.0	0.0	1.9	1.0	0.2	0.2	0.7	0.4
	PP → PNt	0.6	0.0	1.9	1.0	0.5	0.5	1.0	0.5
	SU → NU	0.0	0.0	1.0	0.0	0.0	0.0	0.3	0.0
	SU → MC	0.0	0.6	0.0	1.0	0.5	0.0	0.2	0.5
	SU → PNg	0.6	0.0	0.0	0.0	0.7	0.5	0.4	0.2
	SU → PNt	1.1	1.7	2.9	1.0	1.0	0.7	1.7	1.1
	SU → PP	0.6	0.0	0.0	0.0	0.0	0.0	0.2	0.0
	Total	9.7	4.6	17.1	8.6	18.2	9.5	15.0	7.6

These results demonstrate that GFC facilitated more meaningful conceptual reconstruction than FC. The dominance of the construction category in the experimental group indicates that students were not merely changing their answers but were reorganizing their conceptual frameworks into more scientifically accurate forms (Chi et al., 2018). In contrast, the high proportions of static and disorientation patterns in the control group show that many students were unable to revise or improve their understanding.

The differences between groups can be attributed to the gamified elements integrated into GFC, which stimulated higher levels of cognitive engagement at the interactive level, consistent with the ICAP

framework (Chi & Wylie, 2014). Features such as the collaborate board, video pop-up questions, matching pairs, and time to climb provided visual prompts, immediate feedback, and opportunities for reflection that helped students evaluate their initial ideas and gradually build new concepts (Pacaci et al., 2024). This aligns with the view that cognitive conflict, reflection, and elaboration are essential for deep conceptual change (Treagust et al., 2020).

The decreasing proportions of NU and MC in the experimental group also align with research indicating that GFC can reduce misconceptions while improving students' ability to apply concepts (Majid et al., 2024). Learning conditions that support active participation and allow students to manage their own learning processes contribute positively to conceptual understanding (Uke et al., 2024). Moreover, structured and relevant gamified activities support conceptual reconstruction (Guerrero-Quiñonez et al., 2023), while digital gamified media encourage metacognitive and reflective thinking, enabling students to recognize inconsistencies in their initial conceptions and correct them independently (Siswati et al., 2023).

Overall, the findings demonstrate that while FC can support conceptual change, GFC was more effective in promoting deeper cognitive engagement and more positive conceptual change patterns. By enhancing students' readiness and activation of prior knowledge during the pre-class phase, GFC allowed in-class learning to focus on conceptual consolidation, discussion, and reflection. These results strengthen empirical evidence supporting GFC as a pedagogically grounded and innovative strategy for fostering meaningful learning and conceptual reconstruction in biology education.

CONCLUSION

The findings of this research indicate that the FC and GFC strategies lead to different outcomes in students' cognitive engagement, conceptions, and conceptual change in ecosystem learning, with GFC emerging as the more effective strategy. Students who learned through GFC showed higher levels of cognitive engagement across all indicators, such as interactivity with peers, constructive notetaking, and active processing. Improvements in students' conceptions were also greater among those using GFC, as reflected in the reduced presence of misconceptions and the larger increase in the sound understanding category compared to FC. Patterns of conceptual change among students using GFC were predominantly characterized by construction, whereas students learning with FC exhibited a wider variety of patterns, including static and disorientation. Overall, these results indicate that embedding gamification within the FC model can strengthen students' cognitive engagement and support more meaningful conceptual reconstruction. Based on these findings, several recommendations can be proposed. First, technical limitations experienced by some students when accessing digital learning platforms highlight the need for lightweight and accessible gamification media that align with students' device and network conditions. Second, the design of pre-class learning content should be concise, engaging, and concept-focused to avoid excessive cognitive load. Third, students require more structured exposure to scientific texts; therefore, guided reading activities or scaffolded article analysis may help build this skill gradually. Future studies may also expand the analysis of engagement beyond the cognitive dimension to include behavioral, emotional, and agentic aspects. Additionally, examining the direct relationship between cognitive engagement and conceptual change would offer deeper insight into how engagement contributes to conceptual reconstruction. Finally, the development of open- or semi-open diagnostic instruments is recommended to capture students' misconceptions more accurately and comprehensively.

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