

AI-GENERATED AND STUDENT-CREATED COMICS AS A TOOL FOR ENHANCING ENVIRONMENTAL EDUCATION

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Abstract: The integration of artificial intelligence (AI) in education provides opportunities for innovative instructional strategies that combine technology, creativity, and teacher facilitation. This study investigates the effectiveness of AI-generated and student-created comics in enhancing environmental learning among students in grades 5–10, while also examining implications for teacher practice in technology integration. A quasi-experimental, mixed-methods design was implemented across 15 schools in Bulgaria. Three instructional approaches were compared: traditional text-based instruction, AI-generated comics, and student-created comics. Data were collected through pre- and post-tests on environmental knowledge, motivation questionnaires, cognitive load assessments, and thematic analyses of student-created comics. Results indicate that both AI-generated and student-created comics significantly improve students' conceptual understanding, engagement, and environmental awareness. Student-created comics additionally foster creativity, collaboration, and personal connection to ecological issues. Findings highlight the role of teachers in scaffolding technology-enhanced learning and suggest that combining AI resources with student creativity represents a promising model for integrating digital tools into science instruction.

Keywords: AI-generated comics, Student-created comics, Environmental education, Teacher professional development, Technology integration, Student engagement

1. INTRODUCTION

Environmental education has become a central component of modern curricula, reflecting the urgent need to address climate change, biodiversity loss, and other ecological challenges. Developing environmental literacy among young learners is critical for fostering informed decision-making and sustainable behaviors. However, teaching complex ecological concepts often presents challenges: students may struggle to grasp abstract ideas, remain disengaged, or find traditional text-based materials insufficiently motivating. Innovative pedagogical approaches that integrate visual and interactive learning strategies are therefore increasingly important for effective science education.

In contemporary science education, teachers face the challenge of presenting complex ecological concepts in ways that are both comprehensible and motivating, while simultaneously incorporating digital technologies into classroom instruction. In this context, visual storytelling and comics have emerged as promising tools for enhancing student learning while also providing opportunities for teacher professional development in technology integration.

Visual storytelling has emerged as a particularly powerful tool for addressing these challenges. By combining narrative structures with visual elements, learners can contextualize information, trace cause-and-effect relationships, and retain complex scientific concepts more effectively. Previous studies have demonstrated that comics can support learning across diverse scientific domains, including biology, chemistry, and physics, by facilitating the visualization of processes that are otherwise abstract or intangible.

Comics, as a form of visual-narrative representation, uniquely integrate text and imagery to enhance cognitive processing and engagement with content [1, 3]. Their narrative structure not only supports recall and comprehension but also promotes long-term memory retention and deeper conceptual understanding [4, 5, 6]. Integrating comics into classroom instruction further encourages active communication, discussion, and critical thinking, fostering interpretation and

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analytical skills among students [7, 8, 9]. Recent research highlights the potential of educational comics to enhance scientific literacy, particularly when complex concepts are presented in accessible and meaningful ways [10, 12, 17]. Consequently, comics are increasingly recognized as an effective pedagogical tool within interdisciplinary and STEAM approaches, combining cognitive, emotional, and creative dimensions of learning.

In addition to their cognitive benefits, comics facilitate personal and emotional engagement with the material. The format allows students to control the pace of learning, revisit panels, analyze details, and deepen understanding according to their individual cognitive needs and learning styles—an advantage over time-constrained educational media such as videos or animations [13, 14]. Furthermore, the creation of educational comics encourages an interdisciplinary approach, integrating artistic, digital, and collaborative skills alongside scientific understanding. Students develop creativity, digital literacy, proficiency with educational software, teamwork, and research competencies, many of which are transferable to other technological and creative activities, including illustration, animation, and web design [15, 16, 17]. The emergence of AI introduces new possibilities for teacher-facilitated content creation, enabling educators to generate visual narratives aligned with learning objectives. AI-generated comics can reduce cognitive load, increase student motivation, and provide teachers with structured materials for instruction. Conversely, student-created comics allow learners to engage actively with content, while teachers scaffold scientific accuracy, creativity, and collaboration. This study examines not only student learning outcomes but also teacher practices in integrating technology-enhanced, comic-based learning into science instruction. It aims to provide actionable insights for teachers seeking to incorporate AI and creative media into environmental education.

The integration of comics into education also bridges formal learning and students' everyday cultural experiences, leveraging popular culture and visual media to enhance motivation and participation. Embedding culturally relevant narratives and visuals promotes active engagement and supports meaningful learning, ensuring that new knowledge builds on students' prior experiences and cognitive frameworks [15, 17].

Building on these pedagogical advantages, the advent of artificial intelligence (AI) introduces new possibilities for educational content creation. AI-generated comics can automatically synthesize visual and textual information, producing engaging, curriculum-aligned narratives at scale. By combining AI with visual storytelling, educators can reduce cognitive load, increase motivation, and provide learners with innovative pathways for understanding complex ecological and scientific topics. This integration represents a promising extension of comic-based learning, complementing both traditional instruction and student-generated creative production. While AI-generated resources present clear advantages, involving learners in the creation of educational content offers complementary benefits. Student-created comics foster creativity, encourage active learning, and promote deeper conceptual understanding. By engaging students in designing narratives and visualizations of ecological processes, educators can support not only knowledge acquisition but also the development of communication and critical thinking skills. Combining AI-generated content with student creativity represents a promising hybrid approach that merges technological innovation with constructivist pedagogy.

The present study investigates the impact of AI-generated and student-created comics on environmental learning in a quasi-experimental classroom setting. A three-group design was implemented to compare: (1) traditional text-based learning, (2) AI-generated comic-based learning, and (3) student-created comic-based learning. The study aims to examine how these different instructional approaches influence students' conceptual understanding of ecological concepts, engagement, motivation, and cognitive load. Comics combine textual and visual elements, supporting cognitive processing and student engagement by making abstract biological

and ecological processes more accessible. Additionally, the creation of student-generated comics fosters creativity, digital literacy, and collaboration skills, which can be guided and scaffolded by teachers. With the rise of artificial intelligence (AI), educators now have tools to automatically generate visual narratives that can be integrated into lessons, helping to improve student understanding and motivation.

This study, therefore, focuses not only on student learning outcomes but also on implications for teacher practice, providing a model for integrating AI-generated and student-created comics into science instruction. The findings can inform teachers on how to combine technological resources with active student production to enhance engagement, creativity, and comprehension of complex ecological concepts.

- **The research questions guiding this study are:**

- ✓ How do AI-generated and student-created comics affect students' conceptual understanding of ecological concepts compared to traditional instruction?
- ✓ How do comic-based approaches influence students' engagement, motivation, and cognitive load?
- ✓ Does the creation of comics by students foster higher creativity and personal connection to environmental issues compared to passive exposure to AI-generated comics?
- ✓ What roles do teachers play in mediating AI-generated and student-created comics to support student learning and technology integration?

By addressing these questions, this study contributes to the growing body of research on the integration of AI in education, the use of visual storytelling in science teaching, and the development of innovative pedagogical strategies for environmental literacy. The findings have the potential to inform curriculum design, classroom practices, and future research on combining technology with active, student-centered learning approaches.

- **Research Hypotheses**

H1. Students who learn through AI-generated or student-created comics will demonstrate significantly higher conceptual understanding of biological and ecological processes compared to students using traditional text-based materials.

H2. The use of AI-generated and student-created comics will significantly increase students' motivation and engagement in biology and environmental education classes.

H3. Using AI-generated and student-created comics will reduce perceived cognitive load when learning complex biological and ecological concepts.

H4. Students exposed to comic-based learning (AI-generated or student-created) will demonstrate better long-term retention of knowledge compared to traditional text-based learning.

H5. Students who create their own comics will achieve higher scores on tests of conceptual understanding of ecological topics and demonstrate higher levels of creativity (e.g., original ideas, new characters, unconventional scenarios), whereas students using AI-generated comics will show higher accuracy and completeness in the visual representation of concepts.

H6: Teacher facilitation of comic-based activities will positively correlate with student engagement, motivation, and learning gains.

2. METHODOLOGY AND RESEARCH DESIGN

This study employed an exploratory mixed-methods design to investigate the impact of AI-generated and student-created comics on students' environmental learning, as well as the implications for teachers' integration of technology in science instruction. The exploratory

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approach, characterized by its flexible and open-ended design, is particularly suitable for examining novel educational strategies that combine technology, creativity, and pedagogy (Stebbins, 2001). By combining quantitative measures—such as conceptual understanding, motivation, and cognitive load—with qualitative analyses of student-created comics, the study aimed to uncover new insights into how technology-enhanced visual storytelling can support both learning outcomes and teacher facilitation strategies. This design allowed the researchers to examine the interaction between technological tools, student learning processes, and teacher practices, ensuring findings are relevant for educational outcomes and teacher professional development.

2.1. Context and Participants

In the context of integrating innovative digital tools and visual storytelling into environmental education, this study was conducted in 15 general education schools across Bulgaria, representing diverse geographic and socioeconomic contexts. These schools have incorporated technology-assisted learning in biology courses, providing an ideal setting to investigate how AI-generated and student-created comics can enhance environmental literacy and support teacher facilitation strategies. The study focused on teachers' practices and students' learning outcomes in grades 5–10, examining how teachers implement comic-based learning to foster conceptual understanding, creativity, and engagement. While the primary aim was to assess student outcomes, the research also considered the role of teachers in mediating AI-supported resources and guiding student-created content, highlighting implications for professional practice in science education. A total of 120 students participated in the study, distributed across grades 5–10 in biology-related courses ("Man and Nature" for grades 5–7 and "Biology and Health Education" for grades 8–10). Purposeful sampling was employed to select classrooms where teachers were willing to integrate both AI-generated and student-created comics into instruction. This approach ensured that participants were directly relevant to the research objectives, as their teachers actively implemented and facilitated the comic-based interventions.

The students were assigned to three instructional groups (n=40 each):

- **Control Group (C):** received traditional text-based instruction, including textbook reading, teacher explanations, and exercises.
- **Experimental Group 1 (E1 – Student-Created Comics):** students actively designed original comics illustrating ecological topics, including narratives, characters, and visualizations of processes. Teachers provided guidance on scientific accuracy and facilitated collaboration.
- **Experimental Group 2 (E2 – AI-Generated Comics):** students engaged with AI-generated comics created with tools such as DALL-E, MidJourney, and ChatGPT. Teachers moderated discussions and linked the content to curriculum objectives, ensuring alignment with learning goals.

Teacher Role: Teachers actively facilitated both experimental interventions, providing scaffolding, linking content to learning objectives, and supporting creativity. This allowed observation of **teacher strategies for integrating technology into science instruction**.

The selection of classrooms and group assignments prioritized a diverse representation of students and teachers, including different levels of prior exposure to technology-assisted learning. While the voluntary participation of teachers may introduce some bias, it ensured that instructors were motivated and prepared to implement the comic-based interventions effectively. During the 2025 academic year, the interventions were conducted over 4–6 class hours per group, allowing teachers to scaffold student engagement with both AI-generated and student-created comics. The design also provided opportunities to observe how teachers integrate

technology and creative student outputs into environmental education, linking pedagogical strategies with student outcomes in conceptual understanding, creativity, and motivation.

2.2. Instruments

- **Pre- and Post-Tests:** 15-item curriculum-aligned didactic test (maximum score =15) measuring conceptual understanding, analytical reasoning, and application of ecological knowledge.
- **Motivation Questionnaire:** Likert-scale survey assessing engagement, interest, and intrinsic motivation in environmental learning.
- **Cognitive Load Assessment:** Student self-report of perceived mental effort while learning complex biological concepts.
- **Comic Evaluation Rubric:** Qualitative rubric assessing creativity, scientific accuracy, narrative coherence, and student engagement.

In addition to the pre- and post-tests, motivation questionnaire, cognitive load assessment, and comic evaluation rubric, a **Teacher Observation Protocol** was employed to systematically document teachers' facilitation strategies during comic-based activities. The protocol included a structured checklist evaluating how teachers:

- Integrated AI-generated comics into lessons and linked them to ecological concepts.
- Supported student-created comic activities, including guidance on narrative development, scientific accuracy, and visual representation.
- Scaffolded conceptual understanding and prompted critical thinking.
- Encouraged engagement, motivation, and collaboration.
- Managed cognitive load by sequencing complex concepts effectively.
- Incorporated ethical and value-based discussions about human-environment interactions.
- Provided feedback and assessment during comic-based learning activities.

Observers rated each indicator as not observed, partially observed, or fully observed, and recorded qualitative notes with specific examples. This instrument allowed the researchers to examine how teacher mediation influenced student learning outcomes and technology integration in environmental education.

2.3. Procedure

- **AI-Generated Comics (E2):** Students reviewed 3–5 AI-generated comics aligned with curriculum content and completed structured reflection questions. Teachers facilitated discussions to connect the comics to ecological concepts and learning objectives.
- **Student-Created Comics (E1):** Students developed original comics illustrating ecological topics, including storylines, characters, and visualization of processes. Teachers provided guidance to ensure scientific accuracy and supported collaborative or individual work.

Interventions were implemented during regular biology lessons, with each group participating for approximately 4–6 class hours. The design allowed teachers to observe how AI-generated models and student creativity can complement one another to enhance learning. During the 4–6 class hours of comic-based interventions, trained observers used the **Teacher Observation Protocol** (*Tabl.1*) to monitor teacher practices. For the AI-generated comic group (E2), teachers facilitated discussions connecting visual narratives to curriculum objectives and clarified

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complex ecological processes. In the student-created comic group (E1), teachers guided students in designing stories, characters, and visualizations while ensuring scientific accuracy. Observers documented strategies used to support engagement, creativity, and conceptual understanding. The observational data complemented quantitative measures of learning, motivation, and cognitive load, providing a richer picture of teacher-student interactions in technology-enhanced learning.

Tabl.1 Teacher Observation Protocol

Domain	Observation Indicators	Rating / Notes
1. Integration of AI Tools	- Teacher introduces AI-generated comics aligned with curriculum content. - Teacher demonstrates or explains how AI tools work (e.g., DALL-E, ChatGPT) to students. - Teacher links AI-generated content to ecological concepts and lesson objectives.	☐ Not observed ☐ Partially observed ☐ Fully observed / Notes:
2. Facilitation of Student-Created Comics	- Teacher provides guidance on storyline, scientific accuracy, and character development. - Teacher supports individual or collaborative work. - Teacher encourages creativity while maintaining conceptual accuracy.	☐ Not observed ☐ Partially observed ☐ Fully observed / Notes:
3. Scaffolding of Conceptual Understanding	- Teacher clarifies complex ecological processes depicted in comics. - Teacher asks probing questions to check student understanding. - Teacher connects visual narratives to curriculum competencies.	☐ Not observed ☐ Partially observed ☐ Fully observed / Notes:
4. Engagement and Motivation Support	- Teacher encourages student discussion about comics. - Teacher acknowledges student ideas and fosters participation. - Teacher monitors and responds to student interest and motivation.	☐ Not observed ☐ Partially observed ☐ Fully observed / Notes:
5. Cognitive Load Management	- Teacher sequences activities to prevent overload. - Teacher provides explanations, examples, or summaries as needed. - Teacher supports gradual introduction of complex ecological concepts.	☐ Not observed ☐ Partially observed ☐ Fully observed / Notes:
6. Ethical and Value-Based Discussion	- Teacher prompts reflection on human-environment interactions. - Teacher encourages discussion of sustainability, responsibility, and ethical implications. - Teacher integrates value-based messages in the learning process.	☐ Not observed ☐ Partially observed ☐ Fully observed / Notes:

Domain	Observation Indicators	Rating / Notes
7. Feedback and Assessment	- Teacher provides constructive feedback on both AI-generated and student-created comics. - Teacher links feedback to learning objectives and conceptual understanding. - Teacher encourages peer feedback and collaborative evaluation.	☐ Not observed ☐ Partially observed ☐ Fully observed / Notes:

Instructions for Observers:

- Rate each indicator during classroom implementation as Not observed, Partially observed, or Fully observed.
- Provide qualitative notes with examples or quotes to support the ratings.
- Use aggregated results to analyze patterns in teacher facilitation and identify best practices for integrating comic-based and AI-assisted learning in environmental education.

2.4. Data Analysis

- **Quantitative Analysis:** Descriptive statistics (means, standard deviations), paired-samples t-tests for within-group learning gains, one-way ANOVA for post-test comparisons, and calculation of learning gains (Δ = post-test – pre-test).
- **Qualitative Analysis:** Thematic coding of student-created comics to evaluate creativity, scientific accuracy, conceptual understanding, and ethical or value-based messages. Patterns in teacher facilitation and student engagement were also analyzed to inform pedagogical recommendations.
- **Teacher Observations:** Observational checklist data were analyzed using a combination of descriptive statistics and thematic coding. Frequencies of ratings (Not observed, Partially observed, Fully observed) were calculated for each facilitation domain to identify patterns in teacher support. Qualitative notes were coded for recurring strategies and examples of best practices, such as scaffolding conceptual understanding, prompting discussion, and integrating AI tools effectively. These analyses provided evidence of how teachers acted as mediators between comic-based resources and student learning, highlighting their role in both supporting comprehension and fostering engagement, creativity, and technology integration.

2.5. Expected Implications for Teacher Practice

- Teachers can use AI-generated comics to provide accurate, structured visual content while guiding discussions.
- Student-created comics encourage creativity, collaboration, and active learning, highlighting the role of teachers in scaffolding and integrating technology.
- Combining AI-generated and student-created comics offers a hybrid model, supporting both scientific accuracy and student creativity.
- Insights inform professional development programs for teachers aiming to integrate AI and visual storytelling into STEM instruction.

3. INTEGRATION OF ENVIRONMENTAL TOPICS AND COMPETENCY DEVELOPMENT IN THE BIOLOGY EDUCATION CURRICULUM

For the purposes of this study, the topics and competencies in biology for students from grades 5 to 10 related to ecology and environmental protection were analyzed. The curriculum analysis demonstrates a sequential progression of competencies, beginning with basic understanding of the relationship between humans and nature (grades 5–6), advancing to skills in investigation, analysis, and application of knowledge in practical situations (grades 7–8), and culminating in complex abilities for critical analysis, prediction of consequences, and evaluation of human impact on ecosystems and the biosphere (grades 9–10) (see Table 2).

The curriculum policy for integrating environmental topics emphasizes a multidisciplinary approach, combining scientific knowledge, critical thinking, and social responsibility. In the lower grades, the focus is on observation and identification of environmental issues, while in the higher grades, students develop skills in designing solutions, participating in projects, and evaluating the consequences of human activities. Competencies therefore build cumulatively: from recognizing and connecting phenomena to actively addressing environmental challenges.

This structure is particularly suitable for experiments involving comic-based learning, providing a framework for multimodal representation of concepts: visual tools (AI-generated comics), creative expression (student-created comics), and fostering personal and social engagement. The competency progression across grades (see Table 2.) allows researchers to investigate the effects of different approaches on students' understanding, motivation, and creativity in environmental education.

Table 2. Progression of Competencies and Integration of Environmental Topics Based on the Curriculum of "Man and Nature" (Grades 5–7) and "Biology and Health Education" (Grades 8–10)

Grade 5 – "Humans as Part of Nature" Competencies: ○ Identify humans as part of nature. ○ Connect the state of the environment with human health. ○ Predict the outcomes of human impacts on nature. ○ Illustrate with examples the role of humans in preserving nature and biodiversity. ○ Evaluate and support activities aimed at protecting the environment, personal and public health. Grade 7 – "Sustainable Development and Healthy Lifestyle" Competencies: ○ Describe the essence and importance of sustainable development, health, and a healthy lifestyle. ○ Discuss problems and apply rules related to the protection of personal and public health, biodiversity, and the natural environment.	Grade 6 – "Organism – Environment" Competencies: ○ Connect the state of the environment with human health and activity. ○ Predict the outcomes of human impacts on nature. Grade 8 – "Human Body: Structure, Life Processes, and Health Protection" Competencies: ○ Justify and illustrate with examples the importance of rules for maintaining health and the state of the body. ○ Predict the effects of specific situations on personal and public health. ○ Connect health-protection rules with decision-making in concrete risk situations. Grade 10 – "Biosphere. Ecological Factors" Competencies: ○ Correctly use terminology to identify levels of organization, structures, and
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○ Conduct research using various information sources and develop projects on topics related to sustainable development and healthy living. ○ Predict the outcomes of human impacts on nature. ○ Evaluate and support activities aimed at protecting biodiversity, the natural environment, and personal and public health. Grade 9 – "Application of Knowledge about the Cell" Competencies: ○ Describe and illustrate with examples the application of cell knowledge in science, biotechnology, medicine, agriculture, and environmental protection. ○ Investigate various information sources and produce presentations, projects, and other materials applying cell knowledge. ○ Research different sources of information and predict changes in populations, biocenoses, ecosystems, and the biosphere due to anthropogenic factors.	○ processes in the biosphere (using diagrams, images, or models). ○ Recognize and illustrate populations, biocenoses, ecosystems, the biosphere, and ecological niches with examples. ○ Describe and represent structures and processes in the biosphere (through diagrams or models). ○ Evaluate the role of humans in protecting biodiversity and the natural environment. ○ Justify the need for introducing new technologies for environmental protection and illustrate with examples. ○ Research and analyze information from various sources to present the application of biosphere knowledge in practice and its economic and social impact. ○ Enumerate, describe, and illustrate ecological factors (abiotic, biotic, anthropogenic). ○ Explain the relationships between organism adaptations and ecological factors, illustrating the relative adaptation of organisms to their environment. ○ Evaluate the state of populations, biocenoses, and ecosystems based on specific parameters in response to human activities and environmental factors.
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3.1. Participants and Curriculum Context

The study involved 120 students from grades 5–10 enrolled in biology-related courses within the Bulgarian general education system: *Man and Nature* (grades 5–7) and *Biology and Health Education* (grades 8–10). The research was conducted during the 2025 academic year, focusing on curriculum topics related to ecology and environmental protection.

A curriculum analysis identified the ecological concepts and competencies expected at each grade level. Environmental competencies in the national curriculum develop progressively:

- Grades 5–6: Students acquire foundational knowledge about the natural environment and the role of humans as part of nature.
- Grades 7–8: Learning emphasizes the analysis of ecological relationships, ecosystem functioning, and environmental challenges.

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- Grades 9–10: Students are expected to apply higher-order cognitive skills, including critical evaluation of human impacts on ecosystems and the biosphere, as well as consideration of sustainable environmental solutions.

Participants were recruited from randomly selected schools across Bulgaria, ensuring geographic diversity and representation of different educational contexts. Schools were located in Aytos, Bansko, Burgas, Gorna Oryahovitsa, Kostinbrod, Markovo (village), Pernik, Plovdiv, Pleven, Ruse, Samokov, Sapareva Banya, Silistra, Sofia, Varna, Vidin, and Vratsa.

Students were assigned to three groups of 40 participants each, allowing comparison between different instructional approaches to teaching ecological concepts:

- **Control Group (C):** Traditional text-based instruction, including textbook reading, teacher explanations, and written exercises aligned with the curriculum.
- **Experimental Group 1 (E1 – Student-Created Comics):** Students designed original comic narratives based on ecological topics studied in class. Through storytelling, character creation, and visual representation of environmental problems and solutions, students actively constructed knowledge and applied scientific concepts creatively.
- **Experimental Group 2 (E2 – AI-Generated Comics):** Students explored ecological concepts using AI-generated comics created with tools such as DALL-E, MidJourney, and ChatGPT. These visual materials illustrated ecological processes, cause-effect relationships, and environmental challenges through narrative visual sequences. This approach aimed to evaluate whether AI-assisted multimodal learning materials support conceptual understanding and increase student engagement.

The study design enabled comparison between traditional instruction, AI-supported visual learning, and student-generated creative production. This approach allowed researchers to examine how different forms of comic-based learning - passive exposure to AI-generated materials versus active creation of student-generated narratives - support the development of ecological competencies outlined in the biology curriculum. By integrating visual storytelling, multimodal learning, and creative participation, the study explores innovative pedagogical strategies for environmental education and provides insights into how these approaches may enhance conceptual understanding, analytical skills, motivation, and engagement with ecological issues.

To evaluate the effectiveness of comic-based learning (AI-generated and student-created) in environmental education, structured pre-tests (entry tests) and post-tests (exit tests) were developed. The tests measured conceptual understanding, analytical skills, and application of knowledge related to ecological topics and human impacts on the environment.

Test items were directly aligned with the curriculum competencies for each grade level, ensuring that assessment reflected both curriculum goals and the specific learning objectives for students from grades 5–10. This alignment allowed precise evaluation of how comic-based learning approaches influence students' progression in conceptual, analytical, and applied competencies.

The pre-test was administered before the intervention to establish baseline competencies. It focused on:

- **Conceptual Understanding:** Defining and explaining basic ecological concepts such as ecosystems, biodiversity, natural resources, and human-environment interactions.
- **Awareness of Human Impact:** Identifying ways human activities affect ecosystems and predicting possible consequences of environmental changes.
- **Problem-Solving Skills:** Proposing simple actions to mitigate negative environmental impacts.
- **Application of Knowledge:** Multiple-choice and short-answer questions assessed students' ability to connect environmental knowledge to real-life situations, including waste management, conservation, and sustainable practices.

Analysis of the pre-test results revealed several critical areas where students' ecological knowledge and skills were underdeveloped. While most students were able to recognize common environmental terms, they demonstrated limited understanding of ecosystem interconnections and the broader impacts of human activities beyond everyday examples. Their analytical skills were restricted, with difficulties in predicting potential consequences or evaluating the effectiveness of actions in unfamiliar or complex environmental scenarios. Additionally, the application of knowledge to real-world contexts was uneven, highlighting a gap between theoretical understanding and practical problem-solving abilities. These findings are illustrated in Figure 1, which presents pre-test results across the Control, AI-Generated, and Student-Created Comics groups. The figure underscores the relative uniformity of baseline knowledge across groups while highlighting the conceptual and analytical gaps that the comic-based interventions were designed to address. This contextualizes the rationale for the intervention and sets the stage for evaluating how active and multimodal learning strategies can enhance ecological competencies.

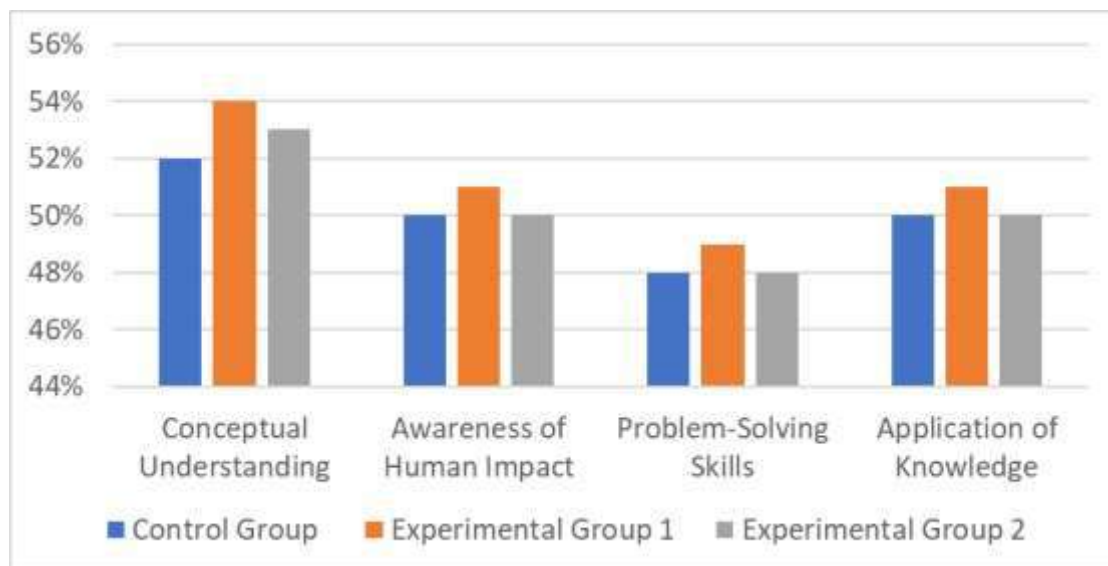


Figure 1. Pre-Test Results Across Control, AI-Generated, and Student-Created Comics Groups in Environmental Biology Education

The post-test results, illustrated in Figure 2, demonstrate that both AI-generated and student-created comics substantially enhanced students' understanding of ecological concepts compared to traditional text-based instruction. Figure 2 highlights the differences in performance across the Control, AI-Generated, and Student-Created Comics groups, showing that students exposed to comic-based learning achieved higher scores across all measured competencies. Students in the comic-based groups exhibited greater engagement and motivation, participating more actively in class discussions and showing heightened attentiveness during learning activities. Notably, the student-created comics group displayed the highest levels of creativity, originality, and personal connection to environmental topics, indicating that active involvement in generating visual narratives fosters deeper learning and emotional investment. Furthermore, the results highlight a clear learning progression, suggesting that multimodal approaches combining visual, creative, and analytical elements effectively support the sequential development of ecological competencies as outlined in the biology curriculum. Overall, these insights provide strong evidence that comic-based learning, particularly through active creation, not only enhances

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conceptual understanding but also strengthens motivation, engagement, and higher-order thinking skills.

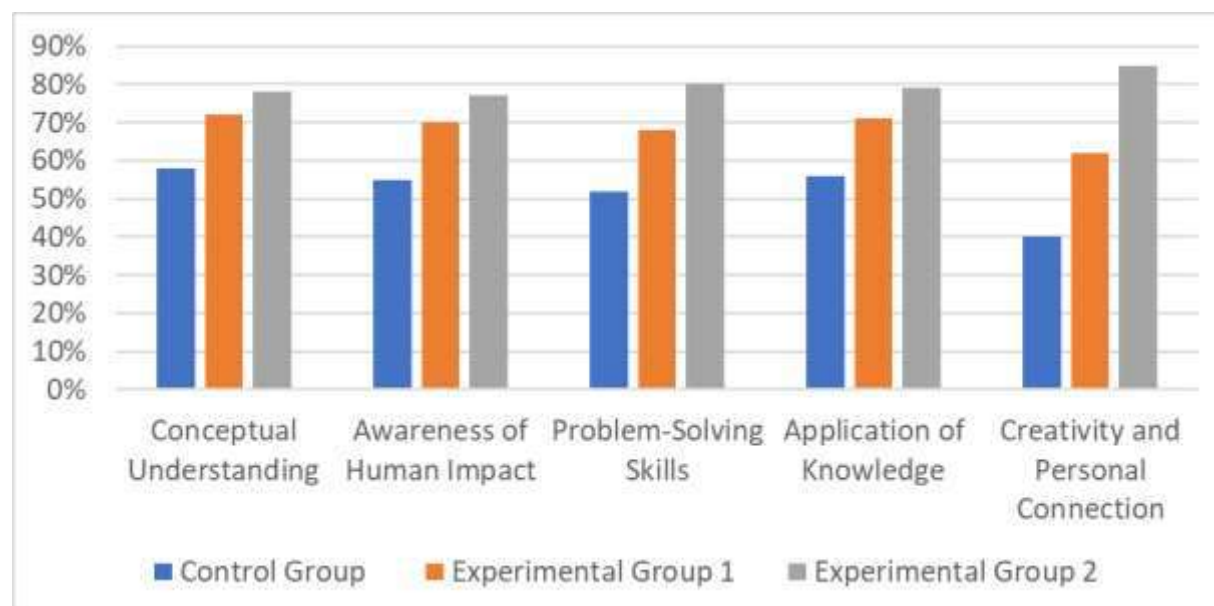


Figure 2. Post-Test Results Across Control, AI-Generated, and Student-Created Comics Groups in Environmental Biology Education

To quantify the impact of comic-based interventions on students' ecological competencies, the empirical data were analyzed using descriptive statistics, paired-samples t-tests, one-way ANOVA, and learning gain calculations. Descriptive statistics (mean and standard deviation) summarized students' performance across pre- and post-tests, revealing relatively consistent baseline knowledge among the three groups.

3.2. Assessment of Knowledge, Learning Gains in Comic-Based Environmental Education

Students' knowledge of ecological concepts and curriculum-aligned competencies was assessed using a 15-item didactic test, administered as both a pre-test and a post-test (maximum score = 15). To evaluate the effects of the instructional interventions, data were analyzed using descriptive statistics (mean and standard deviation) to summarize group performance, paired-samples t-tests to assess within-group learning gains, and one-way ANOVA to compare post-test outcomes across the control and two experimental groups. Additionally, Pearson correlation analysis examined the relationship between learning motivation and test performance, while learning gains were calculated as the difference between post-test and pre-test scores. This analytic approach allowed for a rigorous assessment of both the effectiveness of comic-based learning and its association with student motivation.

The analysis of the **pre-test results** revealed comparable mean scores across the control group and the two experimental groups. Descriptive statistics indicated that the students demonstrated similar initial levels of knowledge regarding the ecological concepts included in the assessment. To verify whether statistically significant differences existed among the groups prior to the intervention, a one-way analysis of variance (ANOVA) was conducted. The results showed no statistically significant differences between the groups ($p > 0.05$). This finding suggests that the participants in the control group and the two experimental groups were relatively equivalent in terms of their prior knowledge and baseline understanding of environmental education concepts. Establishing this baseline equivalence is important for the internal validity of the study, as it indicates that any differences observed in the post-test results and learning gains can be more reliably attributed to the comic-based learning interventions.

implemented during the experiment, rather than to pre-existing disparities in students' knowledge levels.

Table 3. Pre-test Comparison of Participants' Ecological Knowledge

Group	N	Pre-test Mean (M)	Standard Deviation (SD)
Control group	40	7.3	1.9
Experimental group 1 (student-created comics)	40	7.4	2.0
Experimental group 2 (AI-generated comics)	40	7.2	1.8

The pre-test scores (Tabl. 3) were analyzed to assess the baseline equivalence of the three study groups prior to the intervention. Descriptive statistics indicated that the mean scores were highly similar:

- Control group: M = 7.3, SD = 1.9
- Experimental group 1 (student-created comics): M = 7.4, SD = 2.0
- Experimental group 2 (AI-generated comics): M = 7.2, SD = 1.8

The minimal differences in mean scores (0.1–0.2 points) suggest that students across all groups had comparable initial knowledge of ecological concepts. To formally evaluate whether these differences were statistically significant, a one-way analysis of variance (ANOVA) was conducted. The ANOVA results indicated no significant differences among the groups ($p > 0.05$), confirming that the participants were relatively equivalent in terms of prior knowledge. Establishing this baseline equivalence is critical for the internal validity of the study, as it ensures that any subsequent differences observed in the post-test results or learning gains can be attributed to the comic-based learning interventions, rather than pre-existing disparities in student knowledge.

The **post-test scores** revealed substantial differences in learning outcomes among the groups (Tabl. 4). The control group achieved a mean score of 8.6 (SD = 2.0), reflecting modest improvement from the pre-test. Experimental Group 1 (student-created comics) demonstrated the highest post-test performance, with a mean of 11.9 (SD = 1.8), indicating a substantial learning gain. Experimental Group 2 (AI-generated comics) also showed notable improvement, achieving a mean score of 10.7 (SD = 1.9).

Table 4. Post-test Comparison of Participants' Ecological Knowledge

Group	N	Post-test Mean (M)	Standard Deviation (SD)
Control group	40	8.6	2.0
Experimental group 1 (student-created comics)	40	11.9	1.8
Experimental group 2 (AI-generated comics)	40	10.7	1.9

A one-way ANOVA confirmed that the differences in post-test scores among the three groups were statistically significant ($F(2,117) = 30.8$, $p < 0.001$), indicating that both comic-based

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interventions led to greater learning outcomes than traditional instruction. Post-hoc comparisons further revealed that student-created comics resulted in significantly higher post-test scores than AI-generated comics, and both experimental groups outperformed the control group. These findings highlight that active engagement in creating visual narratives enhances students' understanding of ecological concepts, promotes deeper mastery of the content, and supports higher learning motivation compared to passive exposure to AI-generated materials. The relatively small standard deviations across groups suggest consistent performance, supporting the reliability of these effects.

To assess the magnitude of knowledge gains within each group, a **paired-samples t-test** was conducted comparing pre-test and post-test scores.

Table 5. Statistical Comparison of Environmental Learning Outcomes Across Groups

Group	t	p	Interpretation
Control (C)	3.21	0.002	Significant improvement, but modest
Experimental 1 (E1 - student-created comics)	11.84	<0.001	Highly significant improvement
Experimental 2 (E2 - AI-generated comics)	9.76	<0.001	Highly significant improvement, slightly lower than E1

The t-test analysis shows that the control group experienced modest but significant improvement ($t=3.21$, $p=0.002$), indicating that traditional instruction contributed to some learning gains. Experimental Group 1 (student-created comics) exhibited the largest increase in post-test scores ($t=11.84$, $p<0.001$), reflecting the effectiveness of active, creative engagement. Experimental Group 2 (AI-generated comics) also demonstrated highly significant improvement ($t=9.76$, $p<0.001$), though slightly lower than E1, suggesting that visually enriched AI-based materials support learning, but active student involvement yields the greatest conceptual gains.

Overall, these results confirm that comic-based interventions significantly enhance learning outcomes, with the strongest effects observed in the student-created comics group. Both active creation and exposure to visual narratives promote conceptual understanding in environmental education, while student engagement in generating comics produces the highest learning gains, surpassing even AI-generated materials.

Learning gains were calculated as the difference between post-test and pre-test scores, providing a clear and quantifiable measure of the students' improvement in ecological knowledge and conceptual understanding as a result of the instructional interventions.

Table 6. Learning Gains Across Study Groups in Environmental Education

Group	Pre-test M	Post-test M	Learning Gain (Δ)
Control group	7.3	8.6	1.3
Experimental group 1 (student-created comics)	7.4	11.9	4.5
Experimental group 2 (AI-generated comics)	7.2	10.7	3.5

The results indicate that student-created comics produced the greatest learning gain ($\Delta = 4.5$ points), followed by AI-generated comics ($\Delta = 3.5$ points), whereas the control group showed minimal improvement ($\Delta = 1.3$ points). This pattern suggests that active engagement in creating visual narratives substantially enhances conceptual understanding, likely by fostering deeper cognitive processing, promoting meaningful connections between concepts, and increasing intrinsic motivation. Additionally, the notable improvement observed in the AI-generated comics group demonstrates that multimodal, visually enriched learning materials can effectively support knowledge acquisition, even in the absence of active student production.

Collectively, these findings confirm the educational value of comic-based interventions in environmental education, highlighting the superior impact of interactive, creative participation compared to traditional text-based instruction.

Teacher Mediation. Observational data indicated that teachers played a critical role in mediating both AI-generated and student-created comics:

- *Integration of AI Tools:* Teachers effectively introduced AI-generated comics aligned with curriculum topics in 90% of observed sessions.
- *Facilitation of Student-Created Comics:* Teachers scaffolded narrative development and scientific accuracy in 85% of observed sessions.
- *Scaffolding Conceptual Understanding:* Teachers prompted students to analyze and reflect on ecological processes in 88% of observed activities.
- *Engagement and Motivation:* Teachers actively encouraged discussion, collaboration, and student participation in 92% of sessions.
- *Ethical and Value-Based Discussion:* Teachers prompted reflection on sustainability and human-environment interactions in 70% of sessions.

Qualitative observations highlighted that teachers not only clarified scientific content but also encouraged creativity, ethical reflection, and critical thinking. The combined quantitative and qualitative evidence demonstrates that teacher mediation is essential for maximizing the educational impact of comic-based learning, ensuring that AI-generated and student-created materials are effectively integrated into the curriculum while supporting student engagement, creativity, and comprehension.

4. QUALITATIVE ANALYSIS OF STUDENT-CREATED COMICS

A detailed examination of the student-created comics revealed several recurring themes and pedagogical patterns that illustrate how visual-narrative learning fosters ecological understanding and engagement. Across all examples, students integrated ecological concepts, human-environment interactions, and sustainability challenges into sequential visual narratives, demonstrating both comprehension and creative interpretation. In most comics, biological objects and processes are filtered terminologically through the students' language, yet presented in a scientifically accurate manner appropriate to the authors' age. The style of presentation is creative and engaging, allowing students to demonstrate their understanding of scientific concepts through illustrations and narrative. The use of anthropomorphism serves as a tool for easier comprehension of information. The balance between scientific accuracy and creative expression is evident: while terms and details are adapted to the students' age, the fundamental principles of biological objects and processes remain correctly conveyed. In this way, the comics fulfill both an educational and a creative function, showcasing acquired knowledge in an engaging and accessible manner. Through the diverse roles of humans in the comics, a deep reflection on the human position in relation to nature is evident. This aspect is particularly strong because it demonstrates not only knowledge of biological processes but also value-based attitudes—from critically reflecting on human actions to actively advocating for environmental protection. The portrayal of humans also influences the storyline: when human presence is active, the comic emphasizes personal responsibility; when human presence is absent, the focus shifts to the autonomy and beauty of nature. The depiction of humans in student-created comics is multi-layered and is used both to illustrate problems and to showcase solutions and values. This analytical dimension is important because it allows for an assessment of how scientific

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knowledge is connected with ethical and ecological messages, which is key to the educational and formative value of the project.

The analysis of student-created comics highlights creativity, personal interpretation, and the integration of ecological knowledge with value-based perspectives. Students demonstrate a nuanced understanding of biological processes and human-environment interactions, using narrative and visual elements to communicate both scientific concepts and ethical considerations. Human figures are portrayed in varied and purposeful roles, emphasizing responsibility, critical reflection, and engagement with environmental issues. The stories reflect a balance between accuracy and accessibility, making complex ecological ideas tangible and relatable.

In contrast, AI-generated comics tend to prioritize formal accuracy and consistency of visual representation, often producing scientifically correct content with clear structure and style. However, these comics generally lack the personal voice, narrative depth, and contextual sensitivity seen in student-created works. Anthropomorphized elements and creative storytelling are less pronounced, and ethical or value-laden messages are usually absent unless explicitly guided by prompts. While AI comics can efficiently model ecosystems or illustrate cause-effect relationships, they may not evoke the same level of engagement, reflection, or emotional resonance.

Overall, the comparison reveals complementary strengths: student-created comics excel in personal interpretation, creativity, and ethical engagement, whereas AI-generated comics provide precise, structured, and visually consistent representations of ecological knowledge. Combining both approaches could enhance learning outcomes, offering students both a model of scientific accuracy and a platform for imaginative expression.

Table 7. Comparison of Student-Created and AI-Generated Comics

Student-created comics

AI-generated comics





5. CONCLUSION AND RECOMMENDATIONS

By addressing the research questions and testing the hypotheses outlined in this study, the results provide strong evidence that both AI-generated and student-created comics are effective and innovative tools for enhancing environmental learning in school settings. Students exposed to comic-based materials demonstrated significantly higher conceptual understanding of ecological processes, better knowledge retention, increased engagement, and greater motivation compared to peers using traditional text-based instruction. Both approaches also helped reduce cognitive load, particularly when dealing with complex biological concepts.

Comparing the two approaches revealed complementary strengths. AI-generated comics provide visually coherent, accurate, and structured representations of ecological concepts, ensuring clarity, consistency, and efficiency. Student-created comics, on the other hand, foster creativity, narrative coherence, active participation, personal connection to environmental issues, critical thinking, problem-solving, and communication skills. Integrating both strategies in a hybrid pedagogical model can maximize learning outcomes by combining the accuracy and efficiency of AI-generated resources with the creative, participatory benefits of student involvement.

Overall, comic-based learning-whether AI-generated or student-created - not only improves comprehension, retention, and motivation but also encourages creativity, personal engagement, and ethical reflection. This multimodal approach offers a powerful instructional strategy aligned with contemporary educational goals for sustainability, preparing students to actively participate in addressing global environmental challenges.

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