

Effectiveness of digital storytelling comics based on a deep learning approach in enhancing environmental awareness among elementary school students

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Abstract

Environmental awareness in elementary school students generally still focuses on cognitive knowledge, without being followed by reflective understanding or real behavior in daily life. This condition highlights a gap in environmental education practices, particularly the lack of integration between affective and behavioral aspects, indicating a need for a learning strategy that fosters a meaningful attitude of environmental care. This study examined the effectiveness of immersive digital storytelling comics developed based on a deep learning approach in enhancing environmental awareness among elementary school students. The method used is quasi-experimental with a pretest-posttest design model. The research subjects consisted of 34 grade V students at one of the East Jakarta public elementary schools in the even semester of the 2024/2025 school year. The instrument is in the form of an environmental awareness questionnaire compiled based on indicators of environmental care attitudes, supported by observations and interviews. Data were analyzed descriptively, using paired t-tests, and N-Gain calculations. The results revealed a significant increase in environmental awareness, with the average score increasing from 42.06 (pretest) to 83.09 (posttest), and $p < 0.001$. The N-Gain analysis of 71.40% indicates a high level of improvement. These findings demonstrate that integrating digital storytelling comics with a deep learning pedagogical approach effectively fosters environmental understanding, empathy, and pro-environmental behavior among elementary school students.

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1. Introduction

Environmental education in elementary schools has a strategic role in shaping ecological awareness from an early age. This urgency is reinforced by the increasing impact of global environmental crises such as global warming, air and water pollution, and plastic waste accumulation (Yadav et al., 2022). In Indonesia, especially in densely populated urban areas, environmental degradation is reflected in declining air quality, rising waste volume, and shrinking green open spaces (Priyanta & Zulkarnain, 2024; Santoso et al., 2020). As the first formal education setting, elementary schools should be the leading platform for cultivating environmental values through curriculum, learning activities, and school culture. However, environmental education in practice often remains superficial, focusing mainly on cognitive aspects while neglecting affective and behavioral dimensions that shape fundamental attitudes and actions (Dillon & Herman, 2023). This limitation is reinforced by conventional teaching methods that rely heavily on lectures and assignments, causing students to receive information passively rather than engaging with environmental issues in meaningful ways (Meguid & Collins, 2017; Roberts, 2019). Although programs such as Adiwiyata aim to promote environmentally friendly schools, their implementation still faces challenges related to limited facilities, family support, and inconsistency in daily environmental behavior (Aqilah & Lathifah, 2023; Parker et al., 2018).

Field observations further highlight that students' environmental awareness is largely knowledge-based. Many students recognise simple messages, such as "dispose of waste properly," but have not internalised deeper sustainability practices, including the 3R (Reduce, Reuse, Recycle) principles (Debrah et al., 2021; Kiraz & Firat, 2016). They also struggle to connect their daily habits with broader environmental consequences for example, linking single-use plastic consumption to marine pollution or urban flooding. This demonstrates a persistent gap between what students know and how they behave (Gardner et al., 2024). Moreover, students' reflective understanding and practical skills remain underdeveloped. They are not accustomed to sorting waste at home, do not fully understand the health impacts of waste, and are unable to devise simple solutions to environmental problems around them (Ural & Dadli, 2020; Whiley et al., 2017; Aikowe & Mazancová, 2021; Gherheş et al., 2022). These conditions indicate that current environmental learning has not succeeded in fostering deep awareness capable of encouraging real behavior change. Therefore, learning strategies that activate students, promote critical thinking, and situate environmental values in contextual experiences are urgently needed (Suryawati & Osman, 2017).

In response, creative learning media can play a key role in strengthening environmental education. Digital comics combined with storytelling offer visual and emotional engagement that can simplify complex concepts while fostering value internalisation (Puspitarini & Hanif, 2019; Retnowati et al., 2019; Al Faruque, 2023; Zagkotas, 2025). Through relatable narratives, students are encouraged not only to understand environmental issues such as river pollution or the excessive use of single-use plastics, but also to reflect on their relevance to everyday life (Singh-Pillay, 2025). Accordingly, story-based digital comics provide a promising medium for cultivating environmental care attitudes through enjoyable and meaningful learning experiences.

Storytelling in the form of digital comics not only serves to convey information, but also becomes an effective medium to instill the value of environmental concern in elementary school-age children (Nuñez-Janes et al., 2017). Through storylines, characters, conflicts, and problem-solving, students can put themselves in certain situations so that empathy for ecological issues can be formed. This aligns with Bandura's Social Learning Theory, which emphasises that children learn through the process of observing and imitating behavioural models (Ahn et al., 2020; Rumjaun & Narod, 2025). When digital comics present characters that demonstrate eco-friendly actions, students have concrete references to build awareness and internalize sustainability values (Muthukrishnan & Kelley, 2017; Wibowo & Permana, 2023). To prevent the learning process from stopping at the cognitive and empathic aspects alone, a pedagogical approach is needed that encourages students to deeply analyse the content of the story and relate it to real-life actions. In this context, the deep learning approach provides a relevant framework because it focuses on students' ability to understand the root of the problem, analyze the impacts, and formulate solutions to environmental issues (Brahma, 2025; Kovač et al., 2025; Miller & Krajcik, 2019). Through reflection activities, discussions, and active involvement, students are invited to connect the narrative in the comics to the real conditions around them (Matuk et al., 2021).

In addition, the use of digital comic media is also in line with the principles of dual coding and constructivism, where the combination of text and visuals facilitates meaning, information processing, and the formation of a stronger knowledge scheme (Dean & Bertling, 2020). Visualization of environmental problems such as marine animals trapped in garbage or child figures performing environmentally friendly actions strengthens the critical thinking process and encourages the formation of deep mental representations, which are then sharpened through elaboration processes in a deep learning approach. Thus, the integration of Bandura's social model (observation and imitation of behavior), deep learning approach (analysis, reflection, and action), and dual coding and constructivism (meaning through text-visual and knowledge development) forms a comprehensive learning model. This model not only fosters cognitive environmental awareness, but also develops students' affective and psychomotor dimensions. Ultimately, environmental education in elementary schools can evolve from merely transferring knowledge to fostering attitudes and actions that promote environmental care, as evidenced in daily behaviour (Ryan & Aasetre, 2021; Belda-Medina, 2024; Lin & Chang, 2021; Perry et al., 2023).

Although previous research has shown that creative learning media such as comics, animation, and storytelling are effective in increasing students' motivation and understanding in thematic learning most studies still focus on improving cognitive learning outcomes alone, while affective and behavioral aspects of environmental awareness are still rarely explored in depth (Utaminingsih et al., 2024; Weng et al., 2024; Ardoin et al., 2020). In addition, the application of deep learning in environmental education in elementary schools is still limited, even though this approach is believed to foster a more reflective, critical, and action-oriented understanding (Chen et al., 2025). The novelty of this research lies in the integration of digital storytelling comics with a deep learning approach, not only to convey knowledge but also to internalise values and foster an attitude of caring for the environment in elementary school students.

This research has both theoretical and practical significance. Theoretically, this research contributes to the development of basic education studies by offering an innovative learning model that combines creative digital media and a pedagogical approach oriented to deep awareness. Practically, this research can be a reference for teachers in developing environmental learning strategies that are more contextual, interactive, and fun, so that

students not only understand environmental issues but are also encouraged to apply them in their daily lives (Ardoin & Heimlich, 2021; Zimmerman & Weible, 2017). Furthermore, the results of this study are expected to strengthen the implementation of environmental education policies in elementary schools, including the Adiwiyata program, with a more effective approach to build environmental care characters. However, few studies have integrated immersive digital storytelling comics with deep learning pedagogy to foster both cognitive and affective dimensions of environmental awareness in elementary education.

Based on the background and literature review that has been described, the hypothesis of this study is that digital storytelling comics based on deep learning are effective in increasing environmental awareness of elementary school students. To test this hypothesis, this study aims to: (1) analyze the level of students' environmental awareness before and after learning with deep learning approach digital storytelling comics; and (2) evaluate the effectiveness of deep learning approach digital storytelling comics in increasing environmental awareness of elementary school students. This study contributes theoretically by extending the application of deep learning pedagogy to environmental education and practically by providing teachers with an innovative medium to nurture ecological values and sustainable behaviors in young learners.

2. Method

2.1. Research Design

This study employed a quasi-experimental one-group pretest-posttest design, in which a single class received learning using deep-learning-based digital storytelling comics (Ilhan et al., 2021; Lê & Schmid, 2022; Maciejewski, 2020; Miller et al., 2020). A pretest was administered to measure students' initial environmental awareness, followed by a posttest after the intervention (Asli, 2025). This design was selected due to practical constraints that prevented random assignment, as the research utilized an intact classroom. Despite this limitation, the design enables an empirical comparison of students' environmental awareness before and after the learning intervention. To ensure transparency, potential internal validity threats such as testing effects and maturation were considered and managed by maintaining consistent learning conditions throughout the study. The study was conducted during the even semester of the 2024/2025 academic year at a public elementary school in East Jakarta. Desain one-group pretest-posttest can be seen in Figure 1.

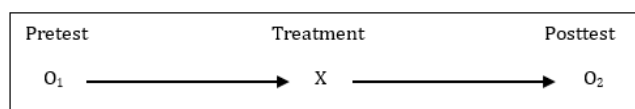


Figure 1. Desain One-Group Pretest-Posttest

2.2. Participants

The participants in this study were 34 fifth-grade students from an elementary school in East Jakarta. The sample was selected using purposive sampling, with inclusion criteria based on curriculum alignment, students' learning readiness, and the relevance of the environmental care theme to their grade level. Fifth-grade students were chosen because their cognitive development has entered Piaget's concrete operational stage, enabling them to understand environmental concepts presented through visual representations and narrative elements in digital comics. All participants and their guardians provided informed consent prior to data collection, and the study received ethical clearance from the institutional research ethics committee. The learning material focused on the theme of Environmental Care, which aligns with the Basic Competencies of the Independent Curriculum.

2.3. Instruments

The instruments used in this study were designed to measure students' environmental awareness before and after the intervention. The instrument consisted of a set of pretest and posttest questions developed based on the dimensions of environmental awareness relevant to elementary school learning. Each item was aligned with specific assessment indicators to ensure content validity. Expert validators in environmental education and elementary science learning reviewed the instrument to assess its relevance, clarity, and alignment with the learning objectives. The detailed of aspects, indicators, and corresponding item numbers is presented in Table 1.

Table 1. Instruments for Validating PreTest and Post Test Questions

Aspects	Assessment Indicators	No Question
Understanding of the concept of biodiversity and environmental sustainability	Understand the meaning of biodiversity.	1, 2, 3, 4, 5, 6, 7
	Explain the importance of forest conservation.	
	Explain the meaning of deforestation.	
	Understand the concepts of sustainability and waste reduction.	

Aspects	Assessment Indicators	No Question
	Identify the impact of environmental damage due to human activities. Describe the changes in the earth due to human activities. Explain the causes of environmental problems.	
Concern for forest and wildlife conservation	Explain the reasons for preserving forests Identify the causes of animal extinction. Understand the meaning of eco literacy.	8, 9, 10
Understanding the impact and prevention of marine pollution	Identify the negative impact of environmental damage. Explain the importance of protecting the ocean from plastic waste. Explain the meaning of microplastics and their sources. Explain the impact of microplastics on the seafood chain. Explain the mechanism of plastic waste eaten by fish.	11, 12, 13, 14, 15
Active participation in environmental protection	Explain how to invite others to contribute to protecting the environment. Explain the reason for sorting waste. Explain the 3R principle. Identify ways to reduce plastic use. Explain how to contribute to protecting the earth.	16, 17, 18, 19, 20
Number of Questions		20

2.4. Data Collection Procedures

Data collection procedures. Data were collected through three complementary methods: (1) an environmental awareness questionnaire administered as a pretest and posttest, (2) structured classroom observations during the intervention, and (3) brief semi-structured interviews after the posttest. The data-collection sequence was as follows:

2.4.1. Instrument development and pilot testing

Items were drafted from the study's four indicators: (a) understanding biodiversity and environmental sustainability, (b) concern for forest and animal conservation, (c) understanding the impact and prevention of marine pollution, and (d) active participation in environmental protection. b. The questionnaire comprised 30 items using a 4-point Likert scale with both positively and negatively keyed statements. c. A pilot study (n = 40) with students of similar characteristics was conducted to evaluate construct validity and reliability.

2.4.2. Validation and reliability

- Content validity was assessed via expert judgment (three specialists in environmental education, educational psychology, and measurement) using the Content Validity Index (CVI). Item-level CVI (I-CVI) averaged .89, and scale-level CVI (S-CVI/Ave) was .91, indicating strong content validity.
- Construct validity was examined with exploratory factor analysis (EFA). The Kaiser–Meyer–Olkin measure was .82, and Bartlett's test of sphericity was significant, $\chi^2(435) = 612.47$, $p < .001$. EFA produced four factors consistent with the theoretical constructs; factor loadings ranged from .52 to .81
- Internal consistency was acceptable: overall Cronbach's $\alpha = .87$; subscale alphas ranged from .78 to .84.

2.4.3. Pretest–intervention–posttest administration

- The validated questionnaire was administered to all participants before the intervention (pretest) and immediately after the intervention (posttest) to measure change in environmental awareness.
- Classroom observations were recorded during teaching sessions to document student engagement (e.g., active participation, verbal responses to stories, and discussion contributions). Observations followed a structured checklist derived from the study indicators. To increase observational rigour and reduce bias, the researcher acted as the session facilitator while an independent observer blind to the study hypotheses simultaneously recorded classroom behaviours. Inter-rater agreement was checked on a subsample of sessions.

- c. Semi-structured interviews were conducted with a purposive subset of students after the posttest to explore reflective understanding and hands-on experiences with the deep learning-based digital comic media.

2.5. Data Analysis

The research data were analysed using both descriptive and inferential statistical techniques, with the assistance of SPSS 26 (IBM, 2020). Descriptive statistics were used to summarise students' environmental awareness before and after the intervention, including the mean and standard deviation (Bergman, 2015). Inferential analysis began with the Shapiro-Wilk test to examine data normality (Singh et al., 2024). When normality assumptions were met, a paired-samples t-test was conducted to determine whether the intervention produced a statistically significant change in environmental awareness, using a significance level of $p \leq .05$. To complement the significance testing, the N-Gain score was calculated to evaluate the magnitude of improvement, which is categorized as high ($g \geq 0.70$), medium ($0.30 \leq g < 0.70$), and low ($g < 0.30$) (Hake, 1999). This combined analysis provided a more straightforward interpretation of the effectiveness of deep-learning-based digital storytelling comics by integrating both statistical differences and the quality of students' learning gains.

3. Results and Discussion

This section presents the effectiveness of deep-learning-based digital storytelling comics in improving elementary students' environmental awareness. Quantitative findings (pretest-posttest differences, normality, homogeneity, t-test, and N-Gain) are integrated with thematic interpretation across four dimensions of environmental awareness: (1) knowledge, (2) attitudes, (3) personal responsibility, and (4) environmentally responsible behaviour. Descriptive analysis results can be seen in Table 2.

Table 2. Descriptive Analysis Results

Statistics	Pretest	Posttest
Mean	42.06	83.09
Median	40.00	85.00
Std. Deviation	16.474	12.493
Variance	271.390	156.083
Range	65	45
Minimum	10	55
Maximum	75	100
Sum	1430	2825

The mean score nearly doubled (from 42.06 to 83.09), indicating substantial improvement after the intervention. The tighter posttest standard deviation shows that students' learning outcomes became more homogeneous. This pattern suggests that the immersive comic effectively supported learners with varying initial abilities. Normality test results can be seen in Table 3 and homogeneity test results can be seen in Table 4.

Table 3. Normality Test Results

Statistics		Kolmogorov-Smirnov			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
The Value of Environmental Awareness	Pretest	.124	34	.200*	.940	34	.062
	Posttest	.138	34	.099	.966	34	.371

Table 4. Table 4. Homogeneity Test Results

Statistics		Levene Statistic	df1	df2	Sig.
The Value of Environmental Awareness	Based on Mean	3.578	1	66	.063
	Based on Median	2.760	1	66	.101
	Based on Median and with adjusted df	2.760	1	62.490	.102
	Based on the trimmed mean	3.628	1	66	.061

Normality and homogeneity tests confirmed that the data met the assumptions for parametric testing (Shapiro-Wilk $p > .05$; Levene's $p = .063$). These results demonstrate that the digital storytelling comic not only improved students' cognitive and affective outcomes but did so consistently across learners. The fulfilment of this assumption strengthens the validity of using subsequent parametric statistical tests, especially paired t-tests, in analysing differences in students' environmental awareness levels before and after treatment with deep learning-based digital storytelling comics. The following are the results of the hypothesis test using the paired t-test can be seen in Table 5.

Table 5. T-Test Results

Paired Samples Test		Paired Differences			t	df	Significance Two-Sided p
		Mean	Std. Deviation	Std. Error Mean			
Pair 1	Pretest - Posttest	-41.029	14.130	2.423	-16.931	33	<.001

The paired t-test results showed a highly significant increase in students' environmental awareness after using deep-learning-based digital storytelling comics. The mean difference between the pretest and posttest was -41.029 (SD = 14.130; SE = 2.423), with a t-value of -16.931, df = 33, and $p < .001$. These findings confirm that the learning intervention had a substantial positive effect, and the research hypothesis is accepted. N-Gain score results can be seen in Table 6.

Table 6. N-Gain Results

N-Gain Results				
	N	Minimum	Maximum	Mean
N-Gain_Persen	34	35.71	100.00	71.4031

Based Table 6, the N-Gain score of 71.40% places the improvement in the high category ($g \geq 0.70$), indicating that the learning intervention had a substantial impact on students' environmental awareness. Together with the significant difference between pretest and posttest ($t = -16.931$; $p < .001$), these results confirm that deep-learning-based digital storytelling comics are effective in enhancing students' environmental understanding, concern, and engagement with environmental issues.

3.1. Understanding of the concept of biodiversity and environmental sustainability

This section discusses the improvement in students' understanding of biodiversity and sustainability. The study's results showed a significant increase in indicators of understanding the concepts of biodiversity and environmental sustainability after the application of *immersive learning-based digital storytelling comics*. These findings indicate that learning media designed with an interactive visual-narrative approach can provide a more contextual and meaningful learning experience for elementary school students. Through the visualisation of characters, flora, fauna, and ecosystem dynamics in the storyline, students gain a concrete understanding of the relationships between ecosystem elements that were previously abstract. The effectiveness of this medium can be explained through the *Dual Coding Theory* proposed by Paivio (1991), which states that information presented in two forms of representation, verbal and non-verbal, allows for long-term memory strengthening. In this context, narrative text and illustrative images in digital comics serve as two complementary channels for information processing. The integration of the two helps students connect verbal concepts (scientific explanations) with visual imagery (ecological representations), making understanding more stable and easier to remember.

The results of the interview, conducted after the posttest, strengthened the quantitative findings. Students demonstrate the ability to identify concrete examples of practices of preserving biodiversity, such as planting trees, not littering, and participating in environmental conservation activities at school. This demonstrates that the learning process through digital comics not only enhances conceptual knowledge but also cultivates an affective dimension, characterised by awareness and concern for sustainability issues. Thus, learning based on *digital storytelling comics* contributes to the development of *ecological literacy* (Orr, 1992), namely the ability to understand the mutual relationship between humans and the environment, as well as the moral responsibility to maintain its balance.

The success of this medium aligns with the *Cognitive Theory of Multimedia Learning*. (Mayer, 2011), which asserts that deep understanding is formed through the process of integrating words and images into a coherent cognitive structure. *Digital comics based on immersive learning* create learning experiences that facilitate *generative processing*, that is, an active mental process in which learners organise and integrate new information with existing knowledge. In research, Cheng and Tsai (2020) found that the integration between visualisation and narrative in science learning significantly improves students' understanding of ecological and sustainability concepts. This happens because the combination of images and narratives helps students map complex phenomena into simpler, concrete, and more meaningful terms.

From the perspective of *Vygotsky's social constructivism*, this result can also be explained through the formation of the *Zone of Proximal Development (ZPD)* that occurs when students interact socially in post-learning discussion activities. Discussions after reading digital comics enable students to interpret the story's content, negotiate meaning, and validate their understanding with peers and teachers. This type of social interaction strengthens the process of internalising concepts, so that learning is not only centred on the individual, but also

on the social dynamics that support the formation of shared meaning. These findings align with the research of Liu et al. (2022), who noted that digital storytelling in the context of environmental education can enhance cognitive understanding while promoting critical awareness of global sustainability issues. Overall, the increase in students' understanding of biodiversity and environmental sustainability indicators reflects the success of *immersive learning-based digital storytelling comics* in integrating cognitive, affective, and social dimensions in harmony. This media serves not only as a means of conveying information but also as a vehicle for immersive learning experiences that allow students to build their knowledge through visual, narrative, and social interactions.

3.2. Concern for forest and wildlife conservation

The study's results showed a significant increase in students' concern for forest and animal conservation after the application of *digital storytelling comic media based on immersive learning*. These findings confirm that a learning approach that combines narrative elements and interactive visuals can foster ecological empathy in elementary school students. Through storylines featuring animal characters, ecological conflicts, and the visual backdrop of degraded forests, students not only gain cognitive knowledge about the importance of ecosystem conservation but also experience a deep emotional connection to the issue.

Observations during the learning process showed an increase in students' enthusiasm in group discussions and reflections on the importance of preserving nature. Students spontaneously associate the learning experience of digital comics with real-life situations in their environment, such as the decline of wild animals or the felling of trees around their residences. This phenomenon demonstrates the emergence of ecological awareness, which is supported by emotional engagement, as described by Fredricks et al (2004). According to this concept, emotional engagement is an important dimension of meaningful learning because it enables students to personally connect with the material, making the knowledge gained not only informative but also motivating real action.

Theoretically, the results of this study can be explained through *the Theory of Narrative Transportation* proposed by Green and Brock (2000). The theory explains that individuals who are "transported" into the storyline will more easily absorb the moral and emotional values contained in it. In the context of this study, students who were actively involved in the stories of forests and animals became more receptive to the ecological messages conveyed. Narratives in digital comics serve as an effective medium that bridges environmental information and emotional experiences, allowing the values of preservation to be transferred more effectively compared to conventional cognitive-oriented learning methods. These findings align with the results of Hung et al.'s (2021) research, which show that digital narrative media can increase ecological awareness and environmental empathy through a process of deep emotional engagement.

Furthermore, the results of this study strengthen the view of Li et al. (2022) that *immersive storytelling* based on digital technology can strengthen pro-environmental *attitudes* in school-age children. Students' emotional engagement through immersive narrative experiences lays the initial foundation for the formation of long-term ecological values and attitudes. This process can be explained through *the Affective Domain Taxonomy* developed by Krathwohl, Bloom, and Masia, which places *receiving*, *responding*, and *valuing* as the initial stages in the internalisation of affective values. In the context of this learning, students first receive moral messages from digital stories, then show emotional responses such as compassion for animals that have lost their habitat, and finally assess the importance of preserving forests as a form of personal responsibility to the environment (Taba, 1965).

The increased concern among students for forest and wildlife conservation found in this study can be understood as a result of a learning process that integrates emotional, cognitive, and value dimensions simultaneously. *Digital storytelling comics based on immersive learning* function not just as an information medium, but as a means of *value-laden learning experience* that allows students to build ecological empathy through identification with characters and narrative situations. This identification process strengthens *moral imagination* (Johnson, 1993), which is the ability to imagine the moral consequences of human actions towards other living things and the surrounding environment. Pedagogically, the success of this model demonstrates that environmental learning based on digital narratives can penetrate the cognitive boundaries of traditional science learning by presenting an emotional and reflective learning experience. When students not only understand the importance of forests and animals intellectually but also feel their significance emotionally, a solid foundation is formed for environmental stewardship, a caring attitude, and a sense of responsibility for nature conservation.

3.3. Understanding the impact and prevention of marine pollution

The study's results showed a significant increase in indicators of understanding the impact and prevention of marine pollution following the application of *immersive learning-based digital storytelling comics*. These findings suggest that interactive narrative-visual learning media can provide elementary school students with concrete, contextual, and meaningful learning experiences. Through visualisations that describe the process of plastic waste entering the sea from land, the destruction of coastal ecosystems, and their impact on marine life,

students gain a holistic understanding of the relationship between environmental components. Digital narratives accompanied by animations and interactive illustrations enable students to understand the cause-and-effect relationship in the phenomenon of marine pollution in a more concrete way than conventional learning, which is often abstract.

The students' involvement in post-learning discussions demonstrated that they were able to relate the content of the stories in the comics to their empirical experiences in the living environment, such as the issue of plastic waste in the river or the habits of people who disregard the cleanliness of the water environment. These findings reinforce the relevance of the *Situated Learning Theory*, as put forward by Lave and Wenger (1991), which emphasises that the learning process is more meaningful when it occurs in a context relevant to learners' real lives. In this context, digital comics serve as a situated context that presents environmental problems within narrative situations that are easily understood by students, ensuring that the knowledge gained is not separate from their socio-ecological reality. Thus, immersive storytelling-based learning can foster ecological awareness rooted in concrete experiences and personal reflection.

From a cognitive perspective, the effectiveness of this media aligns with the *Cognitive Theory of Multimedia Learning*. (Moreno & Valdez, 2005), which explains that a deep understanding is formed when learners actively integrate words (verbal) and images (visual) into a single, coherent mental representation. The visual narrative of ocean pollution not only presents scientific facts but also conveys complex ecological consequences in a clear and structured manner. The combination of text, image, and storyline elements facilitates the occurrence of a *dual coding process*. (Lotfi et al., 2023), in which verbal and non-verbal information reinforce each other's memory storage and knowledge transfer. These results align with the research of Wu et al. (2021), which demonstrates that multimedia-based digital storytelling in environmental education is effective in enhancing students' understanding of the cause-and-effect relationship of pollution while promoting preventive awareness of its impacts. Thus, *immersive learning-based digital comics* not only serve as a means of conveying information but also as a cognitive medium that facilitates students' scientific thinking processes by connecting visual phenomena with abstract ecological concepts.

Furthermore, the results of in-depth interviews indicate that the learning experience through digital comics has triggered the internalisation of values and preventive attitudes towards marine pollution. Students demonstrate awareness of reducing the use of single-use plastics, disposing of waste properly, and maintaining a clean water environment around their homes and schools. This illustrates a shift from conceptual understanding to practical awareness that is applicable in real-world contexts. These findings can be explained through the *Theory of Planned Behaviour* (Ajzen, 1991), which states that a person's behaviour is influenced by intentions formed from understanding, attitudes, and perceptions of self-control. In this context, increasing knowledge about the impacts of marine pollution contributes to the formation of *pro-environmental behavioural intentions*, which can then manifest in concrete actions.

In line with this, Lee et al.'s (2022) research also confirms that integrating immersive learning into environmental education can strengthen the link between cognitive understanding and ecological behaviour in school-age children. Digital media designed in an immersive manner can stimulate ecological empathy through emotional engagement and self-reflection, allowing the knowledge gained to extend beyond the informational level and develop into moral awareness and social responsibility for the sustainability of the marine environment. In the context of basic education, this achievement marks an important initial stage in developing ecological citizenship, a civic identity founded on concern and active participation in maintaining the balance of the Earth's ecosystem. A significant improvement in students' understanding of the impacts and prevention of marine pollution can be attributed to a learning process that integrates cognitive, affective, and social dimensions simultaneously. *Digital storytelling comics based on immersive learning* serve not only as an information medium but also as a vehicle for forming ecological awareness, which involves experiences, emotions, and moral reflection. This learning strategy has proven effective in developing deep conceptual understanding, ecological empathy, and environmentally friendly behaviour intentions in elementary school students, which pedagogically supports the achievement of the goal of sustainable development (*Education for Sustainable Development*).

3.4. Active participation in environmental protection

A significant increase in students' active participation in environmental protection demonstrates the success of immersive learning-based digital storytelling comics in fostering ecological awareness, as evidenced by real-world actions. Based on the results of observations during the learning process, students not only demonstrate involvement in thematic discussions on environmental issues but also exhibit initiative and social responsibility through concrete actions, such as planting trees in the school environment, reducing the use of single-use plastics, and maintaining the cleanliness of rivers near their homes. These findings demonstrate that a learning process designed interactively and contextually can transform students from mere recipients of information to active agents of *environmental change*.

This phenomenon can be explained through the perspective of *Experiential Learning Theory* developed by Kolb (1984), which emphasises that effective learning occurs when students go through four stages of the experience cycle: concrete experience, reflective observation, abstract conceptualisation, and *active experimentation*. In the context of this research, digital comics offer concrete experiences through visual storylines that depict various forms of environmental conservation activities and the real impact of human behaviour on the natural world. Students then reflect on the experience through discussion sessions and group activities, ensuring that the knowledge gained extends beyond the cognitive realm to develop into affective awareness and a commitment to action. The reflective process enables students to construct personal meanings from environmental issues, which ultimately fosters a sense of responsibility and a desire to make a meaningful contribution to the preservation of the natural world.

Furthermore, post-learning interviews revealed that most students stated that they felt personal responsibility for environmental conservation efforts, both at school and at home. This awareness reflects the formation of strong *behavioural* intentions, as described in *the Theory of Planned Behaviour*. (Krueger & Carsrud, 1993). This theory emphasises that behavioural intention is the main determining factor in the realisation of actual behaviour. That intention is formed through the interaction between attitudes towards behaviour, subjective norms, and perceptions of behaviour control. In this context, the understanding gained by students from the comic narrative about the importance of maintaining a balance between marine and terrestrial ecosystems has led to the internalisation of ecological values that encourage the formation of internal intentions and motivations to take *pro-environmental actions*.

The research of (Khan et al., 2025) Supports these findings by showing that the use of interactive digital media in environmental learning plays a crucial role in strengthening ecological intentions and behaviours through increased cognitive and affective awareness. Interactivity in digital media enables students to form an emotional connection with the characters and situations in the story, thereby encouraging them to emulate the positive behaviours displayed. Thus, *immersive learning-based digital storytelling comics* function not only as a tool for conveying information but also as a mediating tool that integrates cognitive, emotional, and social aspects into a comprehensive learning experience. The link between immersive learning and students' ecological behaviour is also strengthened by the results of research by Chang et al. (2022), who found that immersive digital storytelling can increase pro-environmental behaviour through increased *emotional engagement, contextual understanding, and a sense of environmental responsibility*. In this study, students' emotional involvement with characters and conflicts in comic stories plays a crucial role in fostering ecological *empathy* and moral responsibility towards the environment. This confirms that students' active participation in environmental protection is not the result of external instruction or normative encouragement, but rather the outcome of internalising values through meaningful and contextual learning experiences.

Furthermore, the increase in student active participation can be understood within the framework of the affective realm, as stated by Grabinger & Dunlap (2011). According to affective taxonomy, the internalisation of environmental values is an advanced stage of attitude development, namely from simply receiving and responding to the valuing and organisation stage, until finally reaching the characterisation *by value* stage. At this stage, the internalised values become part of the personality system and form consistent behavioural commitments. In the context of this study, the students' active involvement in environmental conservation actions indicates that they have achieved a high level of internalisation of ecological values, where environmental awareness has become an integral part of their self-identity and mindset.

The results of this study confirm that *immersive learning-based digital storytelling comics* have a strategic role in developing students' active participation in environmental protection. Through the integration of narrative experiences, contextual visualisation, and critical reflection, students not only gain a conceptual understanding of environmental issues but are also encouraged to take concrete actions based on internalised values and awareness. This improvement demonstrates the success of immersive learning media in transforming the learning process into a transformational experience that encompasses both cognitive, affective, and conative dimensions. Pedagogically, this reinforces the role of *immersive digital storytelling* as a relevant educational approach to cultivating sustainable ecological character in elementary school students, in line with the goals of Education for Sustainable Development (ESD), which emphasises the integration of knowledge, attitudes, and actions for the sustainability of planet Earth.

4. Conclusion

This study demonstrates that immersive, storytelling-based digital comics have a significant impact on improving elementary students' environmental awareness. Statistical results show a substantial increase in post-test scores, supported by observations and interviews that indicate a deeper conceptual understanding and emotional engagement with environmental issues. The findings expand the understanding of how immersive media can integrate visual, verbal, and emotional components to support meaningful learning. The results also reinforce the importance of experiential and situated learning in cultivating sustainable environmental awareness among young learners. The study suggests that immersive learning-based digital

comics can be effectively incorporated into environmental education. This medium not only enhances conceptual understanding but also promotes active pro-environmental actions, such as maintaining cleanliness, reducing plastic use, and participating in school greening initiatives. Further research should investigate the long-term behavioural effects of immersive digital comics and explore their integration with technologies such as augmented reality (AR) and virtual reality (VR). Future studies may also investigate how teacher facilitation and family involvement contribute to sustained environmental behaviour change.

Author Contributions

All authors have equal contributions to the paper. Wirastusrini Tjakrawerdaja contributed to the conceptualisation, methodology design, data organisation, formal analysis, investigation execution, initial draft writing, and visual representation creation. Firmanul Catur Wibowo provided supervision, validation, and methodological guidance and contributed to writing, reviewing, and editing the manuscript. Cecep Kustandi contributed through supervision, strengthening the theoretical framework, project administration, and writing, as well as reviewing and editing. All authors have read and approved the final version of the manuscript. All authors have read and approved the final manuscript.

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