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Socioscientific issue and digital comic in problem based learning enhances student ecoliteracy toward UNESCO Global Geopark conservation

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ABSTRACT

The Toba Caldera region, designated as a UNESCO Global Geopark, requires continuous efforts to preserve its environment and strengthen the ecoliteracy of its community. This study investigated improvements in students' ecoliteracy, including knowledge, environmental caring attitudes, and pro-environmental behaviors, through the use of problem based learning (PBL) integrated with geopark socioscientific issues (GSSI) presented in a digital comic (Comdigi) format. A total of 156 junior high school students in the Toba Caldera area participated in the study. A total of 78 students learned through direct instruction (DI), and 78 received PBL with GSSI in Comdigi. Ecoliteracy knowledge was measured using a 30-item test, while caring attitude and pro-environmental behavior were assessed using questionnaires with 15 items each. The results showed that PBL integrated with GSSI in Comdigi significantly outperformed DI in enhancing ecoliteracy knowledge 39.80%, caring attitudes 49.8% and in pro-environmental behaviors 12.50% with N-gain score of 0.71. These findings confirm that incorporating GSSI in a Comdigi based PBL model effectively strengthens students' ecoliteracy related to the Toba Caldera UNESCO Global Geopark (TCUGGp).

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1. INTRODUCTION

As of April 2025, UNESCO has designated 229 global geoparks across 50 countries, including 12 in Indonesia. One of these is the Toba Caldera UNESCO Global Geopark (TCUGGp), an area internationally recognized for its geological, biological and cultural uniqueness. As a global geopark, the Toba Caldera requires continuous environmental preservation and community awareness to ensure its sustainable utilization. The long-term sustainability of the region is strongly influenced by the extent to which its residents demonstrate environmental responsibility and awareness, commonly referred to as ecoliteracy.

To strengthen local ecological awareness, the UNESCO executive board has recommended the development of interactive educational programs in schools and communities within the Toba Caldera area, including the establishment of Toba Caldera corners. These efforts aim to foster ecoliteracy from an early age, encouraging students to cultivate environmentally responsible attitudes and pro environmental actions. Despite these initiatives, the Toba Caldera Geopark continues to face various environmental problems that

signal limited community ecoliteracy. Recent studies have reported recurring issues such as forest fires, deforestation, flash floods, landslides, water pollution, excessive floating net cages (KJA) and illegal mining [1], [2]. These problems underline the need to strengthen environmental awareness, particularly among students living in the geopark area. Enhanced ecoliteracy is expected to shape communities that are capable of protecting, maintaining and sustainably utilizing the Toba Caldera Geopark environment.

Ecoliteracy encompasses three interrelated dimensions: environmental knowledge, caring attitudes, and pro environmental behavior [3], [4]. These cognitive, affective and behavioral components collectively contribute to environmentally responsible individuals [5]–[7]. Low ecoliteracy among students often results in limited awareness and poor engagement with environmental issues [8]. Therefore, educational efforts that strengthen all three dimensions holistically are essential. Recent studies indicate that learning rooted in socioscientific issues (SSI) and especially local socioscientific issues (LSSI) can effectively enhance students' scientific literacy and environmental understanding when combined with problem based learning (PBL) [9]–[14]. Additionally, digital comics (Comdigi) have been recognized as powerful learning media that improve science literacy and ecoliteracy by presenting ecological concepts visually through engaging narratives [15]–[19].

However, several research gaps remain. First, although LSSI, PBL, and Comdigi have each been shown to support environmental learning, very few studies have integrated these three components simultaneously into a single instructional model. Second, research on students' ecoliteracy within the specific context of UNESCO Global Geoparks—especially the Toba Caldera—is extremely limited, despite the region's urgent environmental challenges. Third, previous studies often assessed only one or two components of ecoliteracy, whereas comprehensive assessments that include knowledge, attitudes and behavior together are still scarce. Fourth, studies focusing on students who live in environmentally vulnerable areas such as the Toba Caldera are lacking, even though such regions represent critical contexts for environmental education.

Considering the importance of improving students' ecoliteracy in environmentally sensitive areas and aligning with UNESCO's recommendations for interactive learning initiatives in schools, this study was conducted in three junior high schools within the Toba Caldera geopark area. The purpose of this research is to obtain empirical data on students' ecoliteracy, specifically their knowledge, caring attitudes and pro environmental behaviors related to the TCUGGp. The results of this baseline study will serve as a foundation for designing science learning materials, media, assessments and instructional or book model aimed at strengthening students' ecoliteracy in junior high school science education [15]–[18].

2. METHOD

This study was conducted in public junior high schools (SMP) located within the TCUGGp area. The research population included all state junior high schools in the region, while the sample consisted of 156 seventh-grade students from three junior high schools: SMP Negeri 1 Porsea, SMP Negeri 3 Muara, and SMP Negeri 1 Harian, as shown in Figure 1.

Students were assigned to either the control group, taught using direct instruction (DI) (n=78), or the experimental group, taught using PBL integrated with geopark socioscientific issues (GSSI) presented in a validated Comdigi (n=78). The Comdigi incorporated hot geopark issues such as biodiversity loss, aquaculture waste from KJA, flash floods, landslides, and Lake Toba pollution, and was validated by content and IT media experts ($\bar{X}$=87.73, good). Figure 2 presents a representative sample of the Comdigi that be developed in this study.

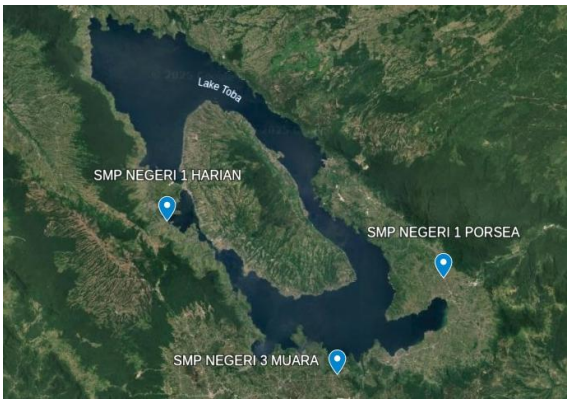

Figure 1. Map of the TCUGGp showing the locations of the three participating junior high schools

Each topic in the Comdigi begins by depicting and presenting environmental problems that occur around students' daily lives, as illustrated in Figures 2(a) and 2(b). These scenes introduce situations such as the occurrence of flash floods and illegal pine tapping in protected forests. By showing events that are close to students' real environments, the Comdigi helps them recognize and understand the environmental issues that exist in their surroundings. After presenting the problem, the story then directs students toward identifying the causes or contributing factors behind these environmental issues, as shown in Figure 2(c). Finally, the Comdigi concludes each topic by presenting possible solutions or actions that students can take to address and prevent these environmental problems, as illustrated in Figure 2(d). The characters encourage simple but meaningful actions, such as picking up trash and disposing of it properly, raising awareness about environmental protection, and developing responsible attitudes toward natural resources.

Figure 2. Sample pages from the Comdigi illustrating GSSI: (a) flash flood, (b) illegal pine tapping, (c) floating net cages (KJA) waste, and (d) pollution

The study was conducted from November 2024 to February 2025 and employed a quasi-experimental pretest–posttest control group design [19]. Instructional activities of PBL-GSSI-Comdigi integration consisted of six steps and were implemented within the ecology unit learning process, covering biodiversity, ecological interactions, environmental change, and conservation. Research data encompassed three domains of ecoliteracy: knowledge, environmental caring attitudes, and pro-environmental behavior, as seen in Figure 3.

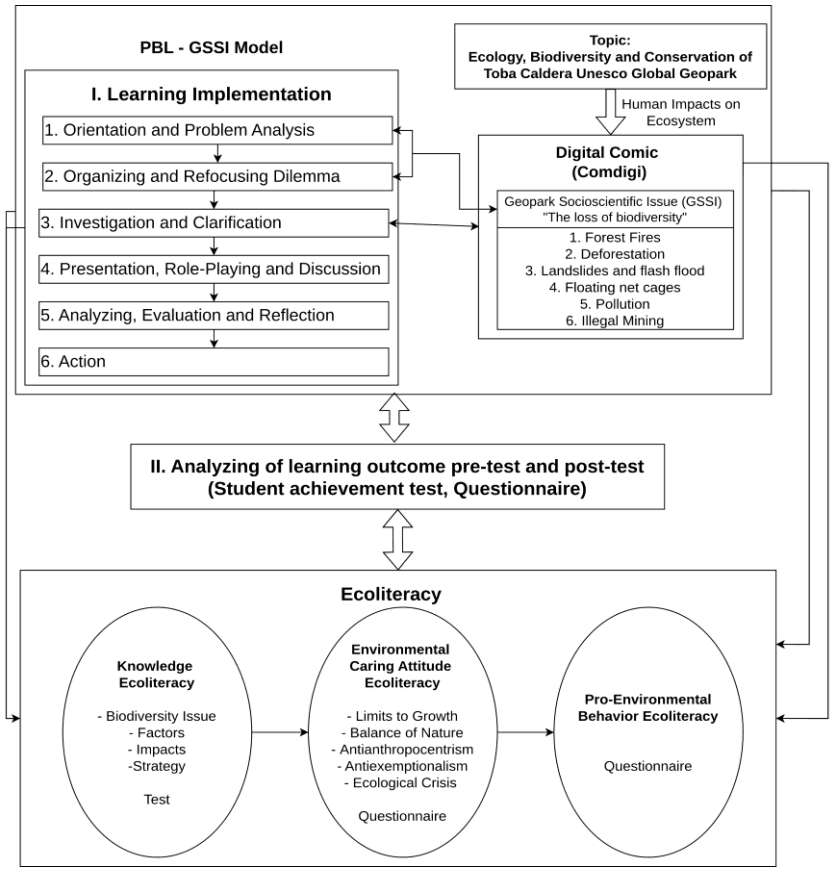

Figure 3. The conceptual framework interaction of PBL, GSSI, and Comdigi to develop the three ecoliteracy dimensions towards geopark conservation

2.1. Knowledge ecoliteracy

Knowledge ecoliteracy was measured using a 30-item assessment comprising 28 multiple-choice questions and two essay items adapted from indicators developed by [20]–[22]. The instrument assessed students' understanding of factual environmental issues occurring in the Toba Caldera, the ecological impacts of these issues, their causal factors, possible mitigation strategies, and knowledge of endemic flora, fauna, and local geosites located near students' homes and schools [2], [23]. The factual issues, impacts, and mitigation indicators contained six items each; causal factors included seven items; and flora–fauna–geosite knowledge comprised 5 items [2]. Expert validation confirmed strong content and construct validity (rxy=0.37–0.55), high reliability (r11=0.86), appropriate difficulty levels (P=0.20–0.80), and adequate discrimination indices (DP=0.33–0.50). Scores were converted to a 0–100 scale and analyzed descriptively and inferentially using t-tests and N-gain [24]. Assumptions of homogeneity (Levene=0.21; p=0.64) and normality (KS=0.13; p=0.20) were fulfilled, and pretest results indicated that the initial knowledge levels of the control and experimental groups were equivalent (t=0.41; p=0.68).

2.2. Environmental caring attitude ecoliteracy

Environmental caring attitude was assessed through a 15-item questionnaire based on the new ecological paradigm (NEP) dimensions, including limits to growth, balance of nature, anti-anthropocentrism, anti-exceptionalism, and ecological crisis [25]. The instrument measured students' beliefs regarding ecological limits, human interactions with natural systems, environmental responsibility, and awareness of

ecological threats in the TCUGGp. Limits to growth is the belief that the earth's limitation to provide natural resources. Balance of nature is the belief that human activity affects natural resources. Anti-anthropocentrism is the belief that humans may could change and control environment. Anti-exceptionalism is the belief that human is responsible to preserve the nature and ecology crisis is the belief that human cause environmental damage. Responses were scored using a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), and the questionnaire demonstrated excellent reliability (r=0.93). Data analysis was conducted using descriptive statistics and the nonparametric Mann–Whitney U test to compare attitudes between instructional groups.

2.3. Pro-environmental behavior ecoliteracy

Pro-environmental behavior was measured using a 15-item Likert-scale questionnaire adapted from North American Association for Environmental Education (NAAEE) [22] and Liang *et al.* [20], assessing students' willingness to act, their ability to apply environmental action strategies and skills, and their participation in responsible environmental behavior related to the preservation of the Toba Caldera. The instrument included 5 items for each indicator and used a 1–4 response scale (4=always, 1=never). Reliability testing indicated excellent internal consistency (r=0.93). Total scores were interpreted using established criteria [26], and descriptive analysis was conducted to evaluate students' behavioral ecoliteracy across groups.

3. RESULTS AND DISCUSSION

3.1. Knowledge ecoliteracy

Based on the data analysis, the mean scores, standard deviations, and ecoliteracy levels of 78 seventh-grade students from three public junior high schools in the Toba Caldera area for both the DI model and the PBL model integrated with GSSI in Comdigi form are presented in Table 1. The homogeneity test indicated that the data were homogeneous (Levene's test: F=0.119; p=0.73), and the normality test confirmed that the data were normally distributed (Kolmogorov–Smirnov=0.104 and 0.065; p=0.055 and 0.200). The data in Table 1 indicated that students' knowledge ecoliteracy regarding the Toba Caldera in the DI class remained within the low or poor category ($\bar{X}$=58.39). In contrast, students in the class taught using the PBL model integrated with GSSI through Comdigi achieved ecoliteracy levels in the high or good category ($\bar{X}$=81.65). It means there was a 39.80% improvement in knowledge.

For the five indicators assessed, the students' knowledge ecoliteracy scores are presented in Table 2. In the DI class, three indicators fell within the low or poor category (impact, factors, and biodiversity), while two indicators were categorized as moderate or sufficient (factual issues and efforts). In contrast, in the PBL class integrated with GSSI using Comdigi–based learning materials, all five indicators were categorized as high or good.

Table 1. Knowledge ecoliteracy of seventh-grade students in the Toba Caldera area (mean, standard deviations, and ecoliteracy levels)

Test	Model	N	Mean	Std. Deviation	Eco level
Posttest	DI	78	58.39	7.13	Low/bad
	PBL	78	81.65	7.34	High/good

Table 2. Comparison of students' knowledge ecoliteracy scores on five indicators related to the Toba Caldera between the DI and the PBL models integrated with GSSI and Comdigi

No	Indicator	DI		PBL	
		Mean±SD	Eco level	Mean±SD	Eco level
1	Factual issue	63.58±11.94	Moderate/enough	83.84±11.19	High/good
2	Impact	58.68±11.14	Low/bad	87.16±11.97	High/good
3	Factors	56.22±11.47	Low/bad	75.42±10.13	High/good
4	Efforts	59.23±13.84	Low/bad	84.35±11.90	Very high/very good
5	Biodiversity	54.10±19.89	Low/bad	76.41±16.97	High/good

Based on the statistical analysis, there was a significant difference in students' knowledge ecoliteracy regarding the Toba Caldera, as seen in Table 3. Students who learned through the PBL model achieved substantially higher ecoliteracy levels compared to those taught using DI. This indicates that the implementation of the PBL model integrated with GSSI through Comdigi media had a highly significant effect on improving students' knowledge ecoliteracy (t=19.77; p=0.00), as in Table 3. A similar pattern was observed for all five knowledge indicators assessed, with t-values ranging from 7.53 to 15.37 (p=0.000).

Table 3. Results of the student's t-test for knowledge ecoliteracy per indicator between DI and PBL with GSSI content

No	Indicator	t-students $_{calc.}$	Probability
1	Knowledge ecoliteracy	19.77	0.00
2	Factual issue	10.92	0.00
3	Impact	15.37	0.00
4	Factors	11.07	0.00
5	Efforts	12.15	0.00
6	Biodiversity	7.53	0.00

Further analysis using the N-gain (g) score produced a value of 0.71. Because this value exceeds 0.70 [24], it indicates that the PBL model integrated with GSSI and supported by Comdigi learning materials was highly effective in improving students' knowledge ecoliteracy concerning the TCUGGp. Higher N-gain values in the experimental class compared to the control class in socioscientific issue–based learning have also been reported by Hanifha *et al.* [26].

The higher ecoliteracy scores observed in the PBL-GSSI Comdigi class compared to the DI class can be attributed to the learning characteristics of the integration of PBL-GSSI model, in which students are required not only to recall information but also to engage in higher-order and critical thinking. This can be seen through the syntax, which includes orientation and problem orientation, organizing and refocusing dilemma, investigation and clarification, presentation, role playing and discussion, analyzing, evaluation and reflection, action [27]. In this study, the problems presented were GSSI such as forest fires, floods and landslides, deforestation, KJA, solid and liquid pollution, and illegal mining [2]. In contrast, the DI model encourages relatively passive learning, where students primarily act as listeners and learning is dominated by teacher lectures.

The influence of the PBL model on improving students' scientific literacy has been reported by [28], [29], while its impact on improving scientific skills has been documented by Pozuelo-Muñoz *et al.* [30] and Uluçinar [31]. Regarding the use of SSI, several studies have shown that integrating PBL with SSI can enhance students' scientific literacy, particularly their critical thinking, decision-making, and reasoning skills. This is because SSI-based learning examines facts and phenomena related to social issues connected to science in real-life contexts [32]. These issues are open-ended, allowing students to think critically while engaging with diverse perspectives. Consequently, students are encouraged to develop higher-order thinking skills and participate enthusiastically in discussions aimed at solving real-world problems [33]. In line with this, several researchers [17], [18], [34] argue that learning through LSSI can strengthen students' ecoliteracy or scientific literacy.

The use of Comdigi as learning resources also contributed significantly to enhancing students' knowledge ecoliteracy. Comdigi present environmental issues through contextual storylines and engaging visuals, helping students understand the relationship between scientific concepts and daily life while stimulating their imagination, thus making abstract ecological concepts easier to comprehend and remember [11], [13], [35]. Moreover, Comdigi containing ecological messages can increase learning motivation and create more meaningful learning experiences, as students become emotionally engaged in understanding environmental problems [36], [37].

3.2. Attitude ecoliteracy

The mean values, standard deviations, and ecoliteracy levels of the environmental care attitudes of 78 students from three public junior high schools located in the Toba Caldera area, under both the DI model and the PBL model with GSSI content supported by Comdigi, are presented in Table 4. Based on the results in Table 4, students' attitude ecoliteracy toward the Toba Caldera in classes taught using the DI model falls into the low or bad category ($\bar{X}$=43.38). In contrast, students taught through PBL with GSSI integrated into Comdigi demonstrated ecoliteracy in the high or good category ($\bar{X}$=64.99). It means there was a 49.80% improvement in attitudes. Furthermore, as shown in Table 5, two indicators in the DI model were categorized as very low or very bad (anti-anthropocentrism and ecology crisis), while the other three indicators were categorized as low or bad (limit to growth, balance of nature, and anti-exceptionalism). Meanwhile, in the PBL model containing GSSI supported by Comdigi, all five indicators fell into the high or good category.

Table 4. Students' attitude ccoliteracy toward the Toba Caldera

	Model	N	Mean	Std. Deviation	Eco level
Posttest	DI	78	43.38	5.12	Low/bad
	PBL	78	64.99	2.94	High/good

Table 5. Comparison of students' attitude ecoliteracy toward the Toba Caldera across five indicators between DI and PBL models

No	Indicator	DI		PBL	
		Mean±SD	Eco level	Mean±SD	Eco level
1	Limit to growth	9.42±1.24	Low	13.29±1.04	High
2	Balance of nature	9.30±1.25	Low	13.20±1.14	High
3	Anti-anthropocentrism	7.57±1.73	Very low	12.47±0.69	High
4	Anti-exceptionalism	9.02±1.48	Low	12.66±0.73	High
5	Ecology crisis	8.05±2.17	Very low	13.34±1.04	High

Based on the statistical test results, there were significant differences in students' attitude ecoliteracy between those taught with the DI model and those taught using PBL integrated with GSSI and Comdigi, as shown in Table 6. Students who learned using the PBL model achieved substantially higher ecoliteracy scores. The Mann–Whitney U, Wilcoxon W, and Z statistics showed a highly significant effect of PBL with GSSI and Comdigi on improving students' attitude ecoliteracy (U/W/Z=1.500/3082.500/10.789; p=0.00). Similarly, all five attitude indicators showed very significant differences favoring the PBL model (U/W/Z=0.000/325.000/6.139 to 2.500/327.500/6.151; p=0.000), as in Table 6.

Table 6. Mann–Whitney U/Wilcoxon W/Z test results for attitude ecoliteracy per indicator between DI and PBL models

No	Indicator	Mann-Whitney U/Wilcoxon W/Z	Probability
1	Attitude ecoliteracy	1.500/3082.500/10.789	0.00
2	Limit to growth	36.000/3117.000/10.747	0.00
3	Balance of nature	62.500/3143.500/10.669	0.00
4	Anti-anthropocentrism	49.000/3130.000/10.840	0.00
5	Anti-exceptionalism	74.000/3155.000/10.690	0.00
6	Ecology crisis	60.000/3141.000/10.643	0.00

The higher attitude ecoliteracy of students toward the Toba Caldera in PBL classes containing GSSI and Comdigi is likely a direct effect of their higher knowledge ecoliteracy. According to Fetiana *et al.* [4], strong environmental knowledge contributes to the development of environmental care attitudes. Environmental attitudes are closely linked to one's knowledge and are shaped by prior understanding. Other studies [38], [39] also noted that better environmental knowledge positively influences individuals' environmental attitudes.

Research also suggests that Comdigi with local wisdom or environmental themes are effective for fostering and strengthening students' environmental care attitudes. These learning tools enhance awareness, concern, and commitment to environmental conservation in schools [40]–[42]. Because the narratives are relevant to students' real-life experiences, the environmental messages become more meaningful, fostering stronger ecological responsibility. Additionally, the visual and narrative strengths of comic media reduce verbal load, allowing students to more easily internalize environmental values within everyday contexts [11], [40]. Based on the questionnaire analysis, qualitative comparisons of students' environmental care attitudes toward the Toba Caldera between those taught with the DI model and the PBL model with GSSI content are presented in Table 7. Clear differences between the two groups are evident.

3.3. Pro-environmental behavior ecoliteracy

Pro-environmental behavior ecoliteracy reflects students' ability to translate their knowledge and attitudes into concrete actions that support ecosystem sustainability. The results of the analysis comparing students taught through DI and those taught using PBL with local or geopark environmental issues presented in Comdigi form are displayed in Table 8. Based on the data in Table 8, students' pro-environmental behavior ecoliteracy in classes taught using DI falls into the moderate category ($\bar{X}$=41.38). Meanwhile, students in PBL classes with GSSI integrated into Comdigi fall into the high or good category ($\bar{X}$=46.55). This indicated that pro-environmental behavior ecoliteracy was higher (around 12.5%) among students who learned through PBL with geopark environmental issues than those in the DI model. Furthermore, the scores for the three indicators assessed are presented in Table 9. For both learning models, the ecoliteracy levels for all indicators fell within the moderate category.

The indicator "strategies and action skills" was the lowest for both learning models. This reflects a gap between students' environmental knowledge and attitudes and the real actions expected to emerge from the learning process. This finding aligns with Liu and Green [43], who reported that increases in environmental literacy and awareness are not always accompanied by changes in actual behavior unless students are provided with opportunities to act, social support, and real field experiences.

Table 7. Comparison of students' environmental care attitudes toward the Toba Caldera between the DI and the PBL models with GSSI

No	Indicator	DI model	PBL model with GSSI
1	Limit to growth	– Do not agree that growth has limits – Do not agree that natural resources are limited – Willing to exploit natural resources without restriction	– Agree that growth has limits – Agree that natural resources are limited and must be used wisely – Will only exploit natural resources within responsible boundaries
2	Balance of nature	– Believe humans may alter the environment according to their needs – Believe humans may use plants and animals freely	– Alter the environment with caution – Use plants and animals according to proper purposes
3	Anti-anthropocentrism	– Do not agree that animals and plants have equal rights to life – Believe humans are superior, while animals and plants are inferior	– Believe humans, animals, and plants have equal rights to life as God's creations – Do not agree that humans are superior to other living beings
4	Anti-exceptionalism	– Show little responsibility for environmental conservation – Do not reprimand people who cut trees irresponsibly – Prefer using tissue rather than reusable handkerchiefs – Do not use reusable bags when shopping – Do not reprimand peers who litter – Permit land burning for various purposes	– Show responsibility for environmental conservation – Reprimand or remind those who cut trees irresponsibly – Avoid using tissue and are willing to switch to reusable handkerchiefs – Bring and use cloth bags when shopping; avoid plastic bags – Reprimand peers who litter – Do not allow land to be burned for any reason
5	Ecology crisis	– Believe current environmental management in the Toba Caldera is sufficient, so ecological disasters will no longer occur	– Believe larger ecological disasters may occur in the Toba Caldera if management does not improve

Table 8. Students' pro-environmental behavior ecoliteracy toward the Toba Caldera

Test	Model	N	Mean	Std. Deviation	Eco level
Posttest	DI	78	41.38	3.51	Moderate
	PBL	78	46.55	7.29	High/good

Table 9. Comparison of students' pro-environmental behavior ecoliteracy toward the Toba Caldera across three indicators between DI and PBL models

No	Indicator	DI		PBL	
		Mean±SD	Eco level	Mean±SD	Eco level
1	Desire to act	14.01±1.49	Moderate	16.83±3.80	Moderate
2	Strategies and skills	13.22±1.64	Moderate	13.92±2.03	Moderate
3	Active participation	14.15±2.19	Moderate	15.79±2.47	Moderate

The integration of PBL and geopark socio-scientific issues has proven to be an effective approach to fostering pro-environmental behavior because it provides an authentic and meaningful learning context. Through this approach, students do not merely solve abstract problems but engage directly with geopark environmental issues, such as deforestation, KJA, water pollution, and geosite degradation in the Toba Caldera. Such contextual learning strengthens emotional and social relevance, moral awareness, and ecological responsibility [44], [45].

Theoretically, PBL positions students as active agents who undergo a structured cycle of ecological thinking and acting, involving problem identification, investigation, solution formulation, action, and reflection [27]. This cycle supports the development of critical thinking, problem-solving, and decision-making skills, which are foundational for forming pro-environmental behaviors. Research by Gök and Boncukçu [46] further demonstrated that students engaged in PBL showed improved problem-solving abilities and greater participation in environmental activities compared with students taught through DI.

Meanwhile, the GSSI component serves as a catalyst for social and moral awareness because students are required to consider multiple perspectives and the social impacts of environmental issues. Study by Viehmann *et al.* [45] highlight that SSI-based learning fosters ecological empathy, strengthens responsibility, and encourages sustainability-oriented decision-making. Similarly, Sanchez *et al.* [47] in a meta-analysis of 52 studies, reported that SSI-based learning consistently improves ecological literacy and attitudes, although its impact on pro-environmental behavior is significant only when interventions include action components and reinforcement of social norms.

Statistical tests confirmed significant differences in students' pro-environment behavior ecoliteracy between those taught using DI and those taught using PBL with GSSI, as in Table 10. Across all indicators, students taught with PBL performed better than those taught using DI. These results confirmed that PBL integrated with GSSI has a very significant impact on enhancing students' pro-environmental behavior ecoliteracy (Mann–Whitney U/Wilcoxon W/Z=1319.500/4400.500/6.115; p=0.00).

Table 10. Mann–Whitney U/Wilcoxon W/Z test results for behavior ecoliteracy per indicator between DI and PBL models with GSSI

No	Indicator	Mann-Whitney U/Wilcoxon W/Z	Probability
1	Behavior ecoliteracy	1319.500/4400.500/6.115	0.00
2	Desire to act	1121.000/4202.000/6.849	0.00
3	Strategies and skills	2432.000/5513.000/2.193	0.02
4	Active participation	1781.000/4862.000/4.506	0.00

Although the statistical analysis showed a significant improvement in pro-environmental behavior among students taught through PBL-GSSI compared with DI, the increase was not optimal. Identified barriers include limited school facilities, lack of financial support for environmental action projects, and negative peer norms (e.g., embarrassment or fear of ridicule when performing pro-environmental actions). This is consistent with Liu and Green [43], who emphasized that social factors and opportunities play a more substantial role than knowledge alone in shaping children's ecological behavior. Conversely, several factors support the development of pro-environmental behavior, including authentic field experiences, teacher facilitation of environmental action, school–community collaboration with the geopark authority, and the use of contextual learning media such as Comdigi featuring local or geopark issues. Boncukçu and Gök [48] demonstrated that PBL activities incorporating micro-action projects (e.g., recycling initiatives, clean water campaigns, or biocompost production) significantly increase students' participation and action skills.

Furthermore, appropriate learning resources play a crucial role in strengthening sustainable behavior. As an innovative learning medium, Comdigi have been shown to enhance students' pro-environmental behavior ecoliteracy. Comdigi present practical ecological actions close to students' daily lives, such as proper waste disposal, waste sorting, energy saving, and caring for plants and animals [13]. This visual–narrative approach helps students understand not only why pro-environmental behavior is important but also how to practice it in daily life. The repeated reinforcement of ecological behaviors through engaging stories also fosters sustainable habits and encourages positive peer support [11].

The findings of this study demonstrate that PBL integrated with GSSI and supported by Comdigi learning materials is effective in increasing students' tendencies toward pro-environmental behavior. This approach strengthens the transformation of knowledge into attitudes and subsequently into behavior. The model not only enhances critical thinking but also fosters the internalization of ecological values and skills, manifested in real actions within the Toba Caldera environment. In conclusion, students' behavior ecoliteracy develops optimally when learning goes beyond conceptual understanding to include opportunities for active participation and direct ecological action [45], [47].

4. CONCLUSION

This quasi-experimental study evaluated the effectiveness of SSI and Comdigi in PBL for enhancing ecoliteracy toward TCUGGp among Indonesian junior high school students. Results demonstrated that integration of GSSI and Comdigi in problem based instruction significantly outperformed conventional teaching in developing knowledge, environmental care attitudes and pro-environmental behavior ecoliteracy. These substantially exceeding typical environmental education intervention effects indicated that geopark socioscientific issue and Comdigi in PBL represents a highly effective approach for geopark conservation education. This study demonstrates how authentic GSSI and Comdigi in problem based instruction can be leveraged for UNESCO Global Geopark conservation education, offering a replicable pedagogical model for the 229 global geoparks worldwide facing similar educational challenges. This study also employs comprehensive ecoliteracy assessment encompassing cognitive, affective, and psychomotor dimensions through validated instruments, advancing ecoliteracy measurement methodology.

Nevertheless, this study provides compelling evidence that SSI approach and Comdigi in PBL is a powerful model for developing youth ecoliteracy toward UNESCO Global Geopark conservation. As the global network of geoparks continues to expand and environmental challenges intensify, evidence-based educational approaches are needed to develop the next generation of conservation stewards. Socioscientific pedagogy and Comdigi in PBL model offers significant promise for addressing this critical need, providing hope for the future of geopark conservation and biodiversity protection worldwide.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [BM], upon reasonable request.

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