



Development of STEM-based E-LKPD with the Context of Air Pollution in Samarinda to Improve Environmental Literacy and Critical Thinking Skills of Junior High School Students

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Abstract: This study aims to develop STEM-based E-LKPD to improve environmental literacy and critical thinking skills of eighth grade junior high school students on respiratory system content, with a context of solving air pollution problems caused by waste burning in Samarinda. The background of this study is the low ability of students to relate scientific concepts to local environmental issues and their weak critical thinking and environmental literacy skills in biology learning. The research method used was Research and Development (R&D) with Thiagarajan's 4D (Define, Design, Develop, Disseminate) model. Experts validated the product in subject matter, media, and language, and its practicality was tested through a student response questionnaire. The effectiveness test was conducted using a pretest-posttest control group quasi-experimental design in four public junior high schools in Samarinda (SMPN 1, 7, 19, and 26). The expert validation results showed that the product was highly valid with an average percentage of 91.66%. The practicality test resulted in a very practical category at the dissemination stage (average score of 3.5–3.7). The effectiveness test proved that the experimental group using STEM-based E-LKPD experienced a significantly higher increase in environmental literacy and critical thinking skills compared to the control group, with a medium-high N-Gain category (0.4–0.8) and statistical significance of $p < 0.05$. These findings suggest that anchoring STEM learning in the tangible, local issue of air pollution in Samarinda effectively bridges the gap between abstract scientific concepts and real-world application, thereby fostering deeper environmental literacy and critical thinking. The study concludes that the developed STEM-based E-LKPD is a feasible, practical, and innovative medium aligned with the Merdeka Curriculum and the Sustainable Development Goals.

Keywords: E-LKPD; STEM; environmental literacy; critical thinking; air pollution; respiratory system; Samarinda

Introduction

The 21st century demands an educational paradigm that transcends the mere transmission of factual knowledge, focusing instead on the cultivation of higher-order thinking skills and the development of responsible global citizens. In science education, this translates to an urgent need for pedagogies that

integrate critical thinking and environmental literacy, aligning directly with the Sustainable Development Goals (SDGs) (UNESCO, 2020). In Indonesia, the Merdeka Curriculum promotes a contextual and differentiated approach to learning (Kemendikbudristek, 2022). However, despite this progressive policy, the implementation of integrated approaches like Science, Technology, Engineering, and

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Mathematics (STEM), especially when grounded in local environmental issues, remains limited (Sari et al., 2022).

Studies consistently show that conventional Student Worksheets (LKPD) tend to be procedural and fail to adequately train higher-order thinking skills (Sihombing et al., 2023). This pedagogical gap is reflected in the low critical thinking abilities of Indonesian students, as highlighted by international assessments (Maghfiroh et al., 2023; OECD, 2023). Concurrently, environmental literacy, a multidimensional construct encompassing knowledge, attitudes, and skills towards the environment (Roth, 1992; McBeth & Volk, 2022) is often underdeveloped when learning is decontextualized. Students struggle to relate scientific concepts to the pressing environmental realities in their own communities. For instance, the pervasive issue of air pollution from waste burning in Samarinda, which has significant documented impacts on respiratory health (DLH Samarinda, 2023; Awasthi et al., 2021; Das et al., 2025), remains an untapped, authentic learning context with high scientific and personal relevance for students.

The rapid advancement of digital technology offers a powerful avenue for pedagogical transformation. Electronic Student Worksheets (E-LKPD) present an opportunity to move beyond static, text-based materials towards interactive, multimedia-rich learning experiences that can foster deep, meaningful learning (Fadilah et al., 2023; Prastika et al., 2023). When these digital tools are designed with a STEM approach, their potential is amplified. The theoretical underpinning for this lies in the holistic and integrated nature of STEM education, which, as argued by Bybee (2013) and Sanders (2009), prepares students to solve real-world problems by applying knowledge and skills from multiple disciplines. Furthermore, integrating the systematic Engineering Design Process (EDP) with its stages of asking, imagining, planning, creating, and improving provides a structured framework that inherently scaffolds critical thinking and problem-solving (Cyndirela et al., 2025).

A review of the current literature, however, reveals several critical research gaps that this study seeks to address. First, there is an issue of shallow contextuality. While STEM-based E-LKPDs exist, many utilize generic environmental problems without deeply exploring the underlying physiological or systemic mechanisms (Fithriyah et al., 2022). Second, previous research often exhibits a single-competency focus, measuring improvements in either cognitive outcomes or literacy skills in isolation, rather than their integrated development (Fitra et al., 2022).

Finally, and most importantly for this study, there is a distinct lack of local-specific integration. To date, no known E-LKPD has leveraged the specific, urgent, and

contextually rich issue of air pollution from waste burning in Samarinda as an integrated case study for learning the respiratory system. This represents a missed opportunity to connect classroom learning directly to students' lived experiences, a principle central to Place-Based Education (PBE), which posits that grounding learning in local phenomena enhances relevance, engagement, and deeper understanding (Gruenewald, 2003; Sobel, 2004). Recent work by Maksymkiw (2025) and Miller (2025) further reinforces the power of PBE in fostering environmental motivation and agency by connecting youth to local social-ecological challenges.

Therefore, the urgency and importance of this research are clear. It is not merely an exercise in developing new teaching materials, but a direct response to a convergence of needs: the national curricular demand for 21st-century skills (critical thinking, environmental literacy), the global imperative of Education for Sustainable Development (ESD) (UNESCO, 2020; Annisa et al., 2024), and the local necessity to address a tangible environmental health issue in Samarinda. By developing a STEM-based E-LKPD contextualized with local air pollution data and challenges, this study aims to bridge the gap between abstract scientific concepts (respiratory system) and students' real-world context. This approach is theoretically grounded in the belief that learning is most effective when it is situated in authentic, meaningful problems (Lave & Wenger, 1991). The STEM framework provides the methodological tools for investigation and solution design, while the local context provides the motivation and personal relevance.

This study aims to develop valid, practical, and effective STEM-based E-LKPD to improve students' environmental literacy and critical thinking skills, by raising the issue of air pollution from waste burning in Samarinda as a learning context. The development was carried out using Thiagarajan's 4D model (Define, Design, Develop, Disseminate) and tested on eighth-grade students in four junior high schools. The specific objectives were (1) product validation by subject matter, media, and language experts; (2) practicality analysis through user responses; and (3) effectiveness measurement.

This research has a dual contribution is theoretically, it develops a contextual STEM learning model that integrates local issues with biological mechanisms, practically, it provides innovative digital teaching materials that are in line with the Merdeka Curriculum and support education for sustainable development (ESD). By raising pressing local issues, this research not only responds to curriculum demands but also operationalizes the SDGs agenda at the secondary education level.

The STEM (Science, Technology, Engineering, and Mathematics) approach is an important philosophical foundation in this study, as it offers a holistic integration of four disciplines to solve contextual and real-world problems (Sanders, 2009; Bybee, 2013). In the context of respiratory system learning, the STEM approach enables students to not only understand scientific concepts theoretically, but also utilize technology (such as interactive simulations and air quality data), apply engineering principles in designing mitigation solutions, and use mathematics to analyze pollutant data. This integration promotes applied learning that is relevant to everyday life, while also training higher-order thinking skills and environmental literacy in an integrated manner (Astuti et al., 2024; Herdini et al., 2021).

As an operational manifestation of the STEM approach, Electronic Student Worksheets (E-LKPD) were developed as interactive, problem-based digital learning media. E-LKPD does not simply transfer conventional material to a digital format, but is designed with multimedia features, simulations, real-time data, and automatic feedback that facilitate independent and collaborative learning (Fadilah et al., 2023; Prastika et al., 2023). The main characteristic of STEM-based E-LKPD is its ability to present real-world problems immersively, such as the issue of air pollution in Samarinda, so that students can explore, analyze data, and design solutions in a structured manner through the systematic Engineering Design Process (EDP) stages (Cyndirela et al., 2025).

Environmental literacy in this study is defined as a multidimensional construct that includes knowledge (cognitive), attitudes (affective), and behavioral skills (psychomotor) towards environmental issues (Purnamawati et al., 2023; Ardiansyah & Zubaidah, 2022). Through the STEM approach, students not only understand the impact of air pollution on the respiratory system, but also develop awareness, responsibility, and motivation to engage in real action. Environmental literacy indicators are measured through the ability to identify sources of pollution, analyze health impact data, and design and implement mitigation solutions relevant to the local context (Wulandari et al., 2023).

Critical thinking skills are an important variable in learning outcomes, which are measured through the abilities of analysis, evaluation, inference, explanation, and self-regulation (Facione, 1990; Saputri et al., 2023). The STEM approach, integrated with problem-based learning (PBL) or project-based learning (PjBL), naturally trains these skills through investigation, data processing, and solution design activities (Haris et al., 2025). In the context of air pollution in Samarinda, students are trained to analyze air quality data, evaluate arguments based on evidence, conclude health impacts, and critically reflect on their own thinking processes.

The relationship between STEM-based E-LKPD and improved environmental literacy and critical thinking skills is mediated by mutually reinforcing cognitive, affective, and conative mechanisms. Pollution data analysis activities (science and mathematics) train critical thinking skills, while engagement with real-world problems fosters empathy and environmental responsibility. Engineering solution design provides space for students to translate knowledge and attitudes into real action. Thus, STEM-based E-LKPD serves as a catalyst that creates a learning environment where improvements in environmental literacy and critical thinking skills occur simultaneously and integratively.

Based on the theoretical framework and needs analysis presented above, this study anticipates that STEM-based E-LKPD with the context of air pollution in Samarinda will be considered highly valid and practical by experts and users in the field. Furthermore, it is hypothesized that students who use STEM-based E-LKPD will show a significantly higher increase in environmental literacy and critical thinking skills compared to groups that apply conventional learning. The impact of this intervention is also predicted to have a large effect size, indicating that the use of STEM-based E-LKPD is not only statistically effective but also practically meaningful in developing these two key 21st-century competencies in junior high school students.

Method

The integration of STEM into the human respiratory system and air pollution issues is illustrated in the following table. The table concretizes how each dimension of STEM (Science, Technology, Engineering, and Mathematics) is operationally translated into context-based learning activities on air pollution in Samarinda. This design ensures that the STEM approach is not merely declarative, but truly integrated and applicable in building environmental literacy and critical thinking skills among students. The E-LKPD is designed by integrating the four STEM domains into the context of air pollution in Samarinda and respiratory system material. This integration is summarized in Table 1.

This study uses a Research and Development (R&D) approach with a 4D model (Define, Design, Develop, Disseminate) adapted from Thiagarajan (1974). The Disseminate stage focuses on testing the effectiveness of the product. The research design to test effectiveness is a quasi-experiment with a Pretest-Posttest Control Group Design.

Tabel 1. STEM Integration

Components	Application in E-LKPD
Science	Studying the structure and function of respiratory organs, as well as the mechanisms of disorders caused by pollutants (PM2.5 particles, CO, etc.).
Technology	Utilizing interactive simulations, online air quality data, or software to analyze pollution data.
Engineering	Designing simple solutions to reduce the impact of pollution (e.g., designing campaign posters, proposals for planting pollutant-absorbing plants)
Mathematics	Processing and interpreting quantitative data on air pollution in Samarinda, creating graphs, and calculating the estimated impact.

valid data regarding the effectiveness of the developed learning media.

The number of samples tested for effectiveness was two classes at SMPN 1 (one experimental class and one control class), as well as at SMPN 7, SMPN 19, and SMPN 26 Samarinda, with each school having 27-30 students, for a total sample of 55-60 students per school. The selection of these two classes also allows for a comparison between the group using interactive E-LKPD and the control group using conventional learning methods, with an estimated total of 240 students.

The research procedure followed four 4D stages: (1) Define: analysis of the curriculum, student needs, and the local air pollution context; (2) Design: preparation of a draft of the Google Sites-based STEM E-LKPD and research instruments; (3) Develop: expert validation and two cycles of limited testing through lesson study; (4) Disseminate: implementation of the final product in quasi-experimental learning.

This study used three main instruments to collect data. The first instrument was an expert validation sheet covering aspects of material, media, and language using a 1-4 Likert scale. The validity score was calculated using the formula:

$$K = \frac{F}{(N \times I \times R)} \times 100\% \tag{1}$$

Explanation:

K = Media validity (%)

F = Number of respondent answers

N = Highest score

I = Number of items

R = Number of respondents

Next, student ability test instruments consisting of environmental literacy tests (20 multiple-choice questions) and critical thinking skills tests (5 structured essays) were used as pre-tests and post-tests. Learning outcome improvement was measured using N-Gain:

$$N - Gain = \frac{(Skor Posttest - Skor Pretest)}{Skor Maksimum - Skor Pretest} \tag{2}$$

(Hake, 1998)

Teacher and student response questionnaire regarding the practicality of E-LKPD using a Likert scale of 1-4:

$$p = \frac{f}{N} \times 100\% \tag{3}$$

Explanation:

P = Percentage score

F = Total score obtained

N = Maximum score

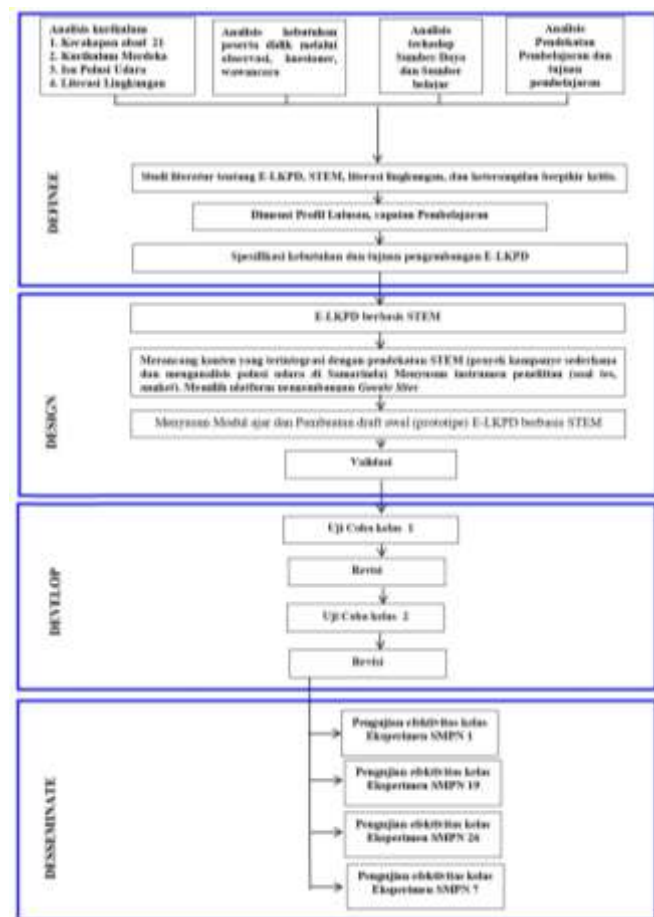


Figure 1. Research Stage

The research sample was taken from the population using purposive sampling, which is the deliberate selection of samples based on certain criteria in accordance with the research objectives. The sample criteria included eighth-grade students who actively participated in learning and were willing to participate in the use of STEM-based interactive E-LKPD. This sample was selected to be representative and to provide

Result and Discussion

The STEM-based E-LKPD product developed was declared highly valid by experts, with an average validation score of 91.97% (Table 2). The practicality test showed an upward trend; from the Less Practical category (score of 2.8) in the initial limited trial, to Very Practical (score of 3.5-3.7) after revisions to improve navigation and clarity of instructions during the dissemination stage in four junior high schools.

Table 2. Expert Validation Results

Validator	Percentage	Category
Media Expert	88%	Highly Valid
Material & Equipment Expert	91.92%	Highly Valid
Language Expert	96%	Highly Valid

The validation results show a very high percentage of validity in all aspects: 96% (language experts), 91.92% (subject matter experts), and 88% (media experts), all falling within the "Very Valid" category. This high level of validity is consistent with the findings of Hidayah & Kuntjoro (2022), who developed a science literacy-based E-LKPD on environmental change and obtained a validity score of 97.22% (very valid). Similarly, Magdalena et al. (2021) reported that an environmental pollution E-LKPD, designed to train critical thinking, achieved a practicality score of 90.4% in the very good category, suggesting that the development of E-LKPD based on environmental problems consistently yields feasible products.

However, a deeper analysis of these scores reveals more than just overall success; it highlights specific design strategies and challenges in developing contextual STEM media. The high linguistic validity stems from the contextualization of the local air pollution issue in Samarinda. By using language close to the learners' lived experiences, the design adhered to the principle of comprehensible input. The strong subject matter validity indicates an accurate and contextual integration of the four STEM dimensions, as well as strong alignment with the Merdeka Curriculum. Meanwhile, media validity, although still highly valid, was the lowest of the three. This reflects technical challenges, such as loading speed and design consistency, underscoring the critical importance of user experience and the supporting technological ecosystem in schools.

The high validity of the product is the result of a rigorous expert appraisal process during the Design and early Development phases, where substantive input from experts is used for refinement prior to empirical testing. This process ensures that the integration of STEM with local issues, designed from the outset, has a

strong theoretical and technical foundation. Thus, achieving high validity is not the end goal, but rather a critical prerequisite that paves the way for testing the practicality and effectiveness of E-LKPD in a real learning context.

The high validity and practicality of the product are the result of an iterative development process that is responsive to user feedback. The design, which is rooted in the local context (air pollution in Samarinda), not only ensures relevance but also builds a sense of ownership among students, which ultimately increases perceived usefulness and ease of use.

Table 3. Results of Student Response Analysis on the Practicality of STEM-Based E-LKPD

School	Score
SMPN 1	3.7
SMPN 7	3.7
SMPN 19	3.5
SMPN 26	3.4
Average Practicality Percentage category	3.5 very practical

The practicality of E-LKPD was assessed through three main dimensions, namely ease of use, utility and relevance to learning objectives, and overall practicality. In general, the majority of students responded positively, ranging from Agree to Strongly Agree, to the various aspects measured. These positive responses were mainly directed at the visual appeal of the E-LKPD, the clarity of the instructions provided, the ease of navigation of the interface, the strong relevance between the issue of air pollution in Samarinda and the material on the respiratory system, and its suitability to the learning styles of students in the digital age.

The increase in the E-LKPD's practicality score from the Less Practical category in the initial trial to Very Practical at the dissemination stage demonstrates the effectiveness of the formative evaluation mechanism and iterative revisions in the 4D development model. Major obstacles in the initial version, such as navigation complexity and ambiguous instructions that increased cognitive load, were successfully identified through user feedback. Revisions focused on simplifying the interface and refining instructions directly targeted usability aspects, resulting in a significant increase in scores. This finding is consistent with the literature review by Perastiati et al. (2026), which concluded that STEM/STEAM-based E-LKPDs are consistently rated as practical and effective in improving critical thinking, especially when supported by interactive media such as animated videos that facilitate the visualization of concepts. It is further reinforced by Indriyani (2024), who implemented a PBL-STEM approach assisted by E-

LKPD on ecology material and reported that the E-LKPD facilitated interactive learning, encouraging students to be more active in the learning process.

Theoretically, this increase in practicality can be explained through the Technology Acceptance Model (TAM), in which technical revisions successfully improved the perception of ease of use. However, a more fundamental factor is the high perceived usefulness, which stems from the contextualization of the local issue of air pollution in Samarinda. The authentic connection between the respiratory system material and the problems that students actually breathe and feel creates strong personal and social relevance. This bridges the cognitive gap between abstract knowledge and real-world application, so that students not only use the media but are genuinely engaged with it.

The convergence of three key factors explains this success are iterative design improvements based on feedback, the power of local context that increases engagement, and alignment with the 21st-century learning paradigm that positions learners as problem solvers. Collaborating with learners as co-designers in the revision process proved to be a highly effective strategy. However, slight variations in scores between schools indicate the influence of supporting ecosystem factors, such as IT infrastructure readiness and teacher digital literacy. This reinforces the findings of Prayitno et al. (2023) that successful implementation depends on the supporting ecosystem, not solely on product quality.

The jump in the E-LKPD's practicality score from the less practical category in the initial trial to very practical in the dissemination stage demonstrates the effectiveness of the formative evaluation mechanism and iterative revisions in the 4D development model. Major obstacles in the initial version, such as navigation complexity and ambiguous instructions that increased cognitive load, were successfully identified through user feedback. Revisions focused on simplifying the interface and refining instructions directly targeted usability aspects, resulting in a significant increase in scores. These findings confirm the paradox that even though students are digital natives, they still need intuitive interface designs and explicit guidance to learn effectively, in line with the research by Purnamawati & Ertikanto (2022).

Thus, high practicality is not only a prerequisite for learning implementation but also a foundation that enables complex and contextual STEM approaches to be accessible and applicable to students. This foundation then facilitates effective learning, as evidenced by significant improvements in environmental literacy and critical thinking skills. This E-LKPD offers a pragmatic and contextual model for biology learning that is

relevant to the actual environmental challenges in urban areas such as Samarinda.

In addition to statistical significance tests, product effectiveness was also measured using Hake's N-Gain analysis (1998) to categorize the magnitude of learning gains from pretest to posttest in each class at four public junior high schools in Samarinda (SMPN 1, 7, 19, and 26). The effectiveness test used a quasi-experimental design. The prerequisite test results showed that the data were normally distributed and homogeneous. Independent sample t-test analysis proved a very significant difference ($p < 0.000$) between the posttest scores of the experimental and control classes in all schools. Furthermore, the N-Gain calculation (Table 4) revealed that the improvement in ability in the experimental class was in the moderate to high category (N-Gain 0.50 - 0.80), which was consistently superior to the control class (N-Gain 0.40 - 0.60).

Table 4. Comparison of N-Gain in Experimental and Control Classes

School	class	N-Gain	Category
SMPN 1	Control	0.6	Moderate
	Experiment	0.8	High
SMPN 19	Control	0.4	Moderate
	Experimental	0.7	High
SMPN 26	Control	0.5	Moderate
	Experimental	0.72	High
SMPN 7	Control	0.4	Moderate
	Experimental	0.5	Moderate

The effectiveness of STEM-based E-LKPD in improving environmental literacy and critical thinking skills has gained strong curricular and empirical legitimacy. Curricularly, the product design is in line with the principles of the Merdeka Curriculum, which has been proven to encourage critical thinking and collaboration skills in the local context of Samarinda (Swandana et al., 2023). Empirically, the research results show a significant increase with a moderate-high N-Gain (0.5-0.8) in the experimental class and a very significant difference ($p < 0.000$) compared to the control class. In-depth analysis reveals that the most notable improvement occurred in the analysis and inference indicators, proving that E-LKPD successfully serves as effective cognitive scaffolding for building a foundation of critical thinking.

This success can be attributed to the multidimensional integration of STEM and the contextualization of authentic local issues. The STEM approach creates a holistic learning experience by combining Science, Technology, Engineering, and Mathematics (Bybee, 2013), which inherently trains critical thinking dimensions such as analysis, evaluation, and inference (Facione, 1990). Meanwhile, the use of the

Samarinda air pollution context as an anchoring point for learning connects the material to the reality of the students, increasing relevance, motivation, and memory retention in accordance with the principles of Place-Based Education (Gruenewald, 2003).

The improvement in environmental literacy occurs holistically, covering the dimensions of knowledge, attitude, and action skills (Roth, 1992; UNESCO, 2017). The activities of analyzing air quality data and designing digital campaigns in E-LKPD simultaneously train problem identification, impact analysis, and solution planning. These findings reinforce similar research while surpassing it by providing an interactive digital platform and rigorous quantitative measurement of critical thinking skills.

The improvement in critical thinking skills, with moderate to high N-Gain scores (0.5-0.8), strengthens the empirical evidence for the effectiveness of the STEM approach in developing higher-order thinking skills. This finding aligns with Badruttamam et al. (2025), who developed an E-LKPD based on Education for Sustainable Development (ESD) and obtained an N-Gain of 0.63 (moderate category) in the experimental group, which was significantly higher than the control group (N-Gain 0.30) ($p < 0.05$). Their study also reported that 50% of students in the experimental group achieved a high N-Gain category, consistent with our finding of scores as high as 0.8. Furthermore, Hasanah et al. (2021), in their implementation of a PBL model combined with a STEM-based LKPD on environmental pollution, reported an increase in critical thinking skills with an N-Gain of 0.93 (high category) and significance of $p < 0.000$. This confirms that integrating STEM with real environmental problems is highly effective in training students' analysis, evaluation, and inference skills. Even the study by Indriyani (2024) showed that the increase in critical thinking in the experimental class (N-Gain 0.55) far exceeded that of the control class (N-Gain 0.34) with a significant difference ($p < 0.000$).

In-depth analysis of our results reveals that the most notable improvement occurred in the indicators of analysis and inference. This proves that the E-LKPD successfully served as effective cognitive scaffolding for building a foundation of critical thinking. This success can be attributed to the multidimensional integration of STEM and the contextualization of authentic local issues. The STEM approach creates a holistic learning experience by combining Science, Technology, Engineering, and Mathematics (Bybee, 2013), which inherently trains critical thinking dimensions such as analysis, evaluation, and inference (Facione, 1990). Meanwhile, the use of the Samarinda air pollution context as an anchoring point for learning connects the material to the reality of the students, increasing relevance, motivation, and memory retention in

accordance with the principles of Place-Based Education (Gruenewald, 2003; Sobel, 2004).

The improvement in environmental literacy also occurred holistically, covering the dimensions of knowledge, attitude, and action skills (Roth, 1992; UNESCO, 2017). The activities of analyzing air quality data and designing digital campaigns in the E-LKPD simultaneously trained students in problem identification, impact analysis, and solution planning. These findings reinforce similar research while surpassing it by providing an interactive digital platform and rigorous quantitative measurement of critical thinking skills.

The sharp difference in results between the experimental and control groups, which only achieved low gains, confirms the fundamental weaknesses of conventional, teacher-centered, textual learning. These findings provide empirical evidence that a contextual approach based on real-world problems is more effective in developing higher-order thinking skills and applied environmental literacy. Implicitly, pedagogical transformation towards integrative, contextual, and learner-centered learning is not only relevant but also a necessity to meet the demands of 21st-century competencies.

The main advantage of this study compared to previous research is the use of the specific context of air pollution in Samarinda as an authentic problem. Previous studies, such as those by Hidayah & Kuntjoro (2022), used a general context of environmental change; Hasanah et al. (2021) used general environmental pollution; and Indriyani (2024) used ecology material. Meanwhile, the literature review by Perastiati et al. (2026) emphasized that the strongest effect of E-LKPD occurs when it is integrated with project-based activities and real-world problems that are close to students' daily lives. The context of air pollution from waste burning in Samarinda provides a stronger personal and social dimension because students directly experience its impact. This aligns with the principles of situated learning and Place-Based Education as articulated by Gruenewald (2003). This explains why the improvement in critical thinking skills in our study (0.8 in several schools) falls into the high category, comparable to the findings of Hasanah et al. (2021) which reached 0.93.

Furthermore, this research contributes to the achievement of the Sustainable Development Goals (SDGs), particularly goal 4 (Quality Education) and goal 13 (Climate Action). Badruttamam et al. (2025) emphasized that the integration of Education for Sustainable Development (ESD) in E-LKPD is effective in improving students' critical thinking skills in the context of environmental issues. Similarly, research published in Sugaku (2024) showed that the STEM-Inquiry model assisted by SDGs-oriented E-LKPD was

effective in improving students' problem-solving skills on environmental pollution material, with an N-Gain of 62.4%. Our findings confirm that when students are confronted with a real environmental problem in their own city (Samarinda air pollution) and are asked to design solutions using a STEM approach, they not only develop critical thinking skills but also the environmental awareness and responsibility that are the core of ESD.

The effectiveness of E-LKPD in improving environmental literacy and critical thinking skills can be explained through the mechanism of contextual STEM integration. This approach transforms students from mere readers of concepts into problem investigators and solution designers. Through activities such as analyzing local pollution data and designing campaigns, they directly practice their analysis, evaluation, and synthesis skills on authentic issues. This is in line with the principles of Place-Based Education, where learning related to the realities closest to learners results in deeper and more meaningful understanding.

These findings have important implications. First, this study successfully demonstrates that the STEM approach does not have to be abstract, but is in fact highly effective when implemented through specific local environmental issues. Second, the resulting product provides a practical model for teachers to implement the Merdeka Curriculum, which emphasizes contextual learning and strengthening the Pancasila Student Profile, particularly in the dimensions of global diversity and mutual cooperation. Thus, this E-LKPD not only addresses the need for innovative learning, but also contributes to education for sustainable development (ESD) at the local level.

Conclusion

Based on the entire research process and data analysis, it can be concluded that the STEM-based E-LKPD developed within the context of air pollution issues in Samarinda meets the criteria as a feasible, practical, and effective learning medium, as evidenced by an average expert validation score of 91.97%, a significant increase in student practicality responses from 2.8 (less practical) to 3.7 (very practical) after iterative revisions, and statistical effectiveness in improving students' environmental literacy and critical thinking skills, with the experimental class achieving significantly higher N-Gain scores (0.5–0.8) compared to the control class ($p < 0.000$), particularly in the indicators of analysis and inference. This study not only succeeded in producing an innovative digital teaching tool that addresses contextual learning needs but also provides empirical evidence that integrating STEM with local

environmental issues serves as an effective strategy for enhancing 21st-century competencies, offering an adaptable model for developing similar teaching materials in different contexts and recommending future research to explore its impact on other skills such as collaboration and creativity.

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Author Contributions

Nurlaila conceptualized the research idea, designed of methodology, management and coordination responsibility; Elsie Theodora Maasawet, and Akhmad, Herliani, Masitah, Lambang Subagiyo analyzed data, conducted a research and investigation process; conducted literature review and provided critical feedback on the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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