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Development of STEM–based Arduino MQ-2 worksheet to improve students' critical thinking

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ABSTRACT

This study aimed to develop and evaluate the validity, practicality, and effectiveness of a STEM-based Student Worksheet integrating Arduino MQ-2 to enhance students' critical thinking skills in investigating air pollution. This Research and Development study employed the Four-D model with 38 Biology Education students selected through purposive sampling. Data were collected using validation sheets, response questionnaires, implementation observations, and pretest-posttest instruments covering six critical thinking indicators. Descriptive analysis and N-Gain were used to evaluate the worksheet. Results showed a validity score of 93.50% (very valid), 100% implementation across STEM components, and student responses ranging from 94.73% to 100% (very practical). The mean score increased from 70.16 on the pretest to 95.76 on the posttest, with an N-Gain of 0.85 (high). Therefore, the developed worksheet is valid, practical, and effective in enhancing students' critical thinking skills.

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Introduction

Critical thinking is a vital higher-order thinking skill in the 21st century because it helps individuals analyze evidence-based information, understand issues more deeply, and make more logical decisions; fact-based argumentation learning has been shown to strengthen these skills (Sarıgöz, 2023). Critical thinking skills are a key part of the 4C competencies—critical thinking, communication, collaboration, and creativity—that students need, especially when studying biology (Amrianto et al., 2024). In the field of education, critical thinking includes six indicators used by students, namely understanding the meaning of information (interpretation), analyzing relationships between concepts (analysis), assessing the strength of evidence (evaluation), drawing logical conclusions (inference), explaining the reasons or results of thinking (explanation), and reflecting on and correcting their own thinking processes (self- regulation) (Facione, 2015).

However, students' critical thinking skills in Indonesia remain relatively low, especially in biology, underscoring the need for systematic efforts to improve them. Data from the Programme for International Student Assessment (PISA) on critical thinking skills in Indonesia show that almost no students excel in science, with only a few reaching Level 5 or 6 (OECD average: 7%) (OECD, 2023). A similar condition is also found in biology learning on environmental pollution, where students still have difficulty analyzing problems, relating pollution to human activities, and writing and drawing scientific conclusions (Amaditha et al., 2024). Critical thinking skills of students in air pollution topics remain generally medium to low, with an average score of 36.13 out of 0–100, reflecting their abilities in problem analysis (Analysis) and drawing evidence-based conclusions (Evaluation) (Arjunaidi & Azid, 2022). This condition is also evident among Biology Education students. A study involving 50 Biology Education students reported that their critical thinking skills were categorized as low, highlighting the need for more systematic and student-centered learning strategies (Nursyamsi et al., 2023).Therefore, biology learning needs to emphasize student or learner activity as a prerequisite for improving critical thinking skills, even though, in practice, learner-centered approaches are still not operating optimally.

Conventional teacher-centered teaching methods lead to suboptimal student engagement in biology, leaving students inadequately prepared to develop their critical thinking skills. Therefore, learning innovations that involve students more are needed (Suryawati et al., 2024). Teachers should use creative methods that include media or technology because studies show that using digital tools to help students think about their own thinking can greatly improve their ability to think critically during learning (Pereles et al., 2024). A relevant strategy for improving critical thinking skills is STEM learning. STEM-based learning provides opportunities for students or learners to conduct direct experiments (integrating STEM) helps solve practical problems, enhancing critical and creative thinking skills essential in the professional world (Khalil et al., 2023).

Research shows that teaching STEM subjects helps students develop their ability to think critically. This is shown by the higher final test scores from the STEM group, which averaged 85.22, compared to the conventional group, which had an average of 76.81. The STEM group had an N-gain score of 0.70, which shows a meaningful difference that is likely not due to chance, as the p-value is 0.023 (Pertiwi, 2024). Therefore, STEM learning needs to be supported by applied learning media that actively engage students in investigating real-world environmental problems. In the context of air-pollution learning, the integration of Arduino MQ-2 gas sensors into a Student Worksheet can provide students with direct access to real-time environmental data, enabling them to collect, interpret, and evaluate evidence related to air quality. Such integration connects STEM concepts with authentic investigation and problem-solving activities, creating opportunities for students to develop critical thinking skills through evidence-based learning.

The STEM approach can be applied by creating contextual learning materials, such as Student Worksheet. In the air pollution material in the Ecology course, the use of STEM-based Student Worksheet integrated with technology, such as Arduino MQ-2 sensors and buzzers, has the potential to help students analyze air pollution phenomena scientifically and practically. Problem-based STEM learning media (distance learning) has been proven to support engagement in the PBL process (average LF of 3.80; good category) and significantly improve critical thinking skills from the "*not* critical" category ($M = -1.54$) to the "critical" category ($M = 17.50$) (N-gain = 0.74), which is considered high and a significant pre-post test ($F = 2374.062$; $p < 0.001$) (Lubna et al., 2023). Using Arduino for STEM lessons, like building sensors, gathering real-world air quality data, and talking about possible solutions, clearly helped students learn better.This is shown by improved math problem-solving skills (Cohen's $d = 0.637$) and a stronger grasp of science ideas (Cohen's $d = 0.804$).This collaborative and project-based learning process is also designed to train critical thinking in analyzing data and formulating solutions to environmental problems (Oh, 2025a).

However, studies that specifically integrate the STEM approach with MQ-2 sensors and buzzers as authentic data sources for learning about air pollution remain relatively limited. The use of Arduino in STEM education has been widely studied, but most studies still treat Arduino primarily as a teaching aid or technical activity rather than as an object of study integrated into students' learning processes. It is essential to develop STEM learning that explicitly integrates the Engineering Design Process with biology education, ensuring that Arduino activities promote higher-order thinking skills rather than existing in isolation (Dat et al., 2024) . Using Arduino in STEM learning to collect real-world air-quality data and discuss potential environmental solutions can provide authentic, data-driven learning experiences that support students' problem-solving and collaborative thinking. However, studies that specifically integrate STEM with MQ-2 sensors and buzzers as authentic data sources for air-pollution learning remain relatively limited (Oh, 2025b).

Therefore, a research gap remains in the integration of Arduino Uno and the MQ-2 gas sensor into STEM-based Student Worksheets that guide Biology Education students to investigate air pollution through authentic data and critical thinking activities. The novelty of this study lies in embedding Arduino MQ-2-based real-time air-quality measurement directly into structured STEM learning activities, enabling students to collect, interpret, evaluate, and use environmental data to investigate air-pollution problems. This integration extends the use of Arduino beyond a technological teaching aid by positioning sensor-generated data as part of students' biological inquiry and critical thinking processes. Accordingly, this study aimed to develop a STEM-based Arduino MQ-2 Student Worksheet on air pollution and examine its validity, practicality, and effectiveness in improving the critical thinking skills of Biology Education students.

Method

This study employed a Research and Development (R&D) method using the Four-D (4D) development model developed by Slamet (2022), which consists of four stages: define, design, develop, and disseminate. The participants were 38 Biology Education students at Universitas Negeri Surabaya enrolled in a General Biology course, selected using a purposive sampling technique based on the criterion that they had not previously completed the air-pollution detection practicum. To evaluate the effectiveness of the developed worksheet, a one-group pretest-posttest design was employed. The worksheet was validated by two expert validators (a media/instructional-design validator and a content/material validator) together with the supervising lecturer. The instruments used to assess validity and practicality were reviewed for content validity by the same expert validators prior to use, and their items were adapted from previously validated worksheet-assessment instruments to support their reliability.

In the educational context, critical thinking consists of six indicators: (1) interpretation, (2) analysis, (3) evaluation, (4) inference, (5) explanation, and (6) self-regulation (Facione, 2015).Critical thinking skills in this study were assessed through test instruments designed to measure students' critical thinking abilities before and after the implementation of the developed worksheet. Three components of analysis were used in the Define stage: concept analysis, task analysis, and student analysis. These analyses were conducted to ensure that the developed student worksheet was aligned with educational standards, student characteristics, learning objectives, and the relevant content. The Design stage concentrated on creating an initial product prototype. In this instance, the design process focused on creating a STEM-based student worksheet that integrated the concepts of science, technology, engineering, and mathematics into a cohesive instructional format.

The Design stage focused on developing a STEM-based student worksheet containing air pollution content, learning activities, Arduino-based experiments using the MQ-2 sensor, and critical-thinking tasks. The Development phase was executed to produce the research output. The output in this research was a STEM-based student worksheet on air pollution developed based on the results of revisions and input from the supervising lecturer and validators. Due to resource and time constraints, the Disseminate stage in this study was limited to a small-scale trial rather than a full-scale dissemination; it involved a limited trial with students enrolled in a General Biology course who had not previously conducted the air pollution detection practicum. There were 38 students from Universitas Negeri Surabaya who participated as respondents in this study. Participants were selected through purposive sampling based on the following enrollment criteria: Biology Education students enrolled in the General Biology course who had never previously taken a laboratory course on air pollution detection. Because this stage constituted a limited-scale field trial rather than a full-scale dissemination, it is more accurately characterized as a preliminary dissemination, and this limited scope is acknowledged later as a constraint of the present study.

The intervention was conducted over 3 meetings, with each meeting lasting approximately 200 minutes. Before the learning activities, students individually completed a pretest to measure their initial critical thinking skills based on the six indicators. The learning activities then followed the STEM-based Student Worksheet, beginning with the identification of an air-pollution problem and discussion of relevant biological concepts. Students subsequently conducted an air-pollution detection activity using an Arduino Uno equipped with an MQ-2 gas sensor and buzzer, collected and recorded the resulting air-quality data, interpreted and analyzed the data, and discussed possible solutions to the identified problem. Before air-pollution measurements were conducted, the MQ-2 sensor was allowed to stabilize for 6 minutes to establish a stable sensor reading. During the calibration period, the sensor reading remained below 100, indicating that the sensor had reached the predetermined measurement condition before data collection. After stabilization, the sensor was used to detect air-pollution conditions during the experimental activities. The resulting measurements were interpreted using the Air Pollution Standard Index (ISPU) categories as the reference for determining air-quality conditions. The ISPU values were classified into five categories: Good (1–50), Moderate (51–100), Unhealthy (101–200), Very Unhealthy (201–300), and Hazardous (≥301). Higher ISPU values indicate poorer air quality and a greater potential impact on human health. These categories were provided in the worksheet as a reference for students to interpret the air-quality data obtained from the Arduino MQ-2 measurements. After completing the worksheet activities, students individually completed the posttest under the same testing conditions as the pretest. The pretest and posttest were completed independently without assistance from other students, and the difference between the scores was used to determine the improvement in critical thinking skills through N-Gain analysis.

The research instruments included validation sheets, student response questionnaires, learning implementation observation sheets, and pretest-posttest questions. The pretest-posttest instrument measured the six critical thinking indicators: (1) interpretation, (2) analysis, (3) evaluation, (4) inference, (5) explanation, and (6) self-regulation (Facione, 2015). The developed worksheet was assessed for validity and practicality using quantitative descriptive analysis, while its effectiveness was determined from the improvement in students' pretest and posttest scores using N-Gain analysis. All quantitative data were processed using Microsoft Excel 2021. The validity sheet used a Likert scale to provide assessments on a scale of 1 (Not valid), 2 (A little bit valid), 3 (Valid), and 4 (Highly valid) (Dika et al., 2025).

The validation data analysis is presented in percentage form, calculated using the following formula (Sugiyono, 2022):

$$\text{Validity Score (\%)} = \frac{Total\ amount\ obtained}{Maximum\ score}\ x\ 100 \tag{1}$$

The validation results, using predetermined validity score criteria, function to assess the practicality of the student worksheet created, as outlined in Table 1 (Sugiyono, 2022).

Table 1. Criteria for validity interpretation.

Score	Description
25-39,9	Invalid
40-54,9	Less valid
55-69,9	Sufficiently valid
70-84,9	Valid
85-100	Highly valid

The practicality of the developed worksheet was assessed based on learning implementation and student responses. The implementation of the STEM-based Student Worksheet was assessed independently by six observers using a structured observation sheet covering the Science, Technology, Engineering, and Mathematics components. All six (6) observers obtained identical scores for each observed component, indicating complete inter-observer agreement. The observation scores were converted into percentages to determine the level of implementation. Student responses were collected using a Guttman-scale questionnaire consisting of positive and negative statements. For positive statements, "Yes" was scored 1 and "No" was scored 0, whereas the scoring was reversed for negative statements. The scores were subsequently converted into percentages to determine the practicality of the worksheet (Sugiyono, 2022).

The acquired score is subsequently determined through the use of the formula provided below:

$$\text{Student Activities} = \frac{\sum total\ score}{\sum maximum\ score}\ \text{x } 100\% \tag{2}$$

$$\text{Response rate} = \frac{\sum students\ answered\ "YES"}{\sum all\ students}\ x\ 100\% \tag{3}$$

The percentages obtained from the research findings were subsequently interpreted according to the score interpretation criteria presented in Table 2.

Table 2. Score interpretation.

Percentage (%)	Criteria
0-37%	Not practical
38-53%	Less practical
54-69%	Quite practical
70-85%	Practical
86-100%	Very practical

Based on the table 2, the standards for the observation results derived from activities and student worksheet responses are deemed practical if the mean score is equal to or greater than 70%, following the practicality threshold commonly applied in R&D-based instructional development studies (Sugiyono, 2022).

The following N-gain score formula was used to student learning data in order to asses the efficacy of learning:

$$\text{N-Gain} = \frac{Posttest\ score - Pretest\ score}{Maximum\ score - Pretest\ score} \tag{4}$$

The students' pretest and posttest results were analyzed based on the predetermined indicators, and the improvement in their critical thinking skills was interpreted according to the N-Gain criteria presented in Table 3. The N-Gain scores were classified into high, moderate, and low categories based on the criteria proposed by Hake (1998). N-Gain analysis was used to determine the extent of improvement achieved by students relative to the maximum possible improvement. This approach is widely applied in science education research because it takes students' initial performance into account, providing a more balanced measure of learning improvement and instructional effectiveness (Nurhidayah et al., 2025), following the normalized-gain approach originally proposed by Hake (1998).

Table 3. N-Gain scoring learning outcome completion.

Gain Coefficient	Description
$g \geq 0{,}7$	High
$0{,}7 > g \geq 0{,}3$	Moderate
$g < 0{,}3$	Low

Results and Discussions

The research results were obtained through review and validation by general biology lecturers and a limited product trial involving 38 Biology Education students at Universitas Negeri Surabaya. The development of this STEM-based student worksheet assisted by an Arduino Uno and MQ-2 sensor was aimed at improving students' critical thinking skills in learning air pollution. The results of the development and validation of the STEM-based student worksheet can be observed in Figure 1.

The outcomes of the LKM development are presented in Figure 1. The LKM includes learning outcomes and learning objectives, along with subtopics that students are expected to achieve. It also provides brief scientific readings on the basic concepts of air pollution to support students' understanding of the material. In addition, the LKM contains explanations of the required tools and materials, as well as the experimental procedures for detecting air pollution using an Arduino and MQ-2 sensor. A YouTube QR code is also provided, directing students to a tutorial video on the air-pollution detection device using Arduino and the MQ-2 sensor. Furthermore, the LKM includes a table for students to record and complete the results obtained from the experiments.

The learning activities in the developed STEM-based Student Worksheet are systematically organized to integrate Science, Technology, Engineering, and Mathematics (STEM) aspects with six critical thinking indicators. The activities begin with the Discussion Activities, in which students analyze air pollution flow diagrams, examine a case study related to SO_2 and pneumonia, and answer analytical questions by relating the information to real-world conditions. These activities primarily involve the Science aspect and develop students' (1) interpretation and (2) analysis skills by requiring them to understand scientific information, identify relationships between air pollutants and their effects, and connect the presented information with environmental and health conditions. The learning activity then continues with the Essential Concepts section, which provides students with fundamental explanations of air pollution, mobile and stationary pollution sources, the Air Pollution Standard Index (ISPU), and the impacts of air pollution. This section provides the theoretical foundation needed before students conduct the practicum. Through these activities, students are encouraged to develop (1) interpretation by understanding the meaning of scientific information and (2) analysis by relating air-pollution concepts, pollution sources, and their potential impacts. The conceptual understanding gained in this section subsequently serves as a basis for students to interpret and evaluate the experimental results obtained during the practical activity. The Practical Activity integrates the four STEM aspects through a hands-on Arduino-based air-pollution detection experiment. Students assemble an air-quality detection device using the Arduino Uno, MQ-2 sensor, LED, and buzzer, calibrate the sensor, observe differences between relatively clean and polluted air conditions, and record the resulting ISPU, LED, and buzzer responses. The Science aspect is developed through the observation and interpretation of air-pollution phenomena, while the Technology aspect is implemented through the use and programming of the Arduino Uno and MQ-2 sensor. The Engineering aspect is demonstrated when students assemble and connect the electronic components, including the MQ-2 sensor, resistors, LEDs, jumper cables, and Arduino Uno, and ensure that the device operates properly. Meanwhile, the Mathematics aspect is incorporated when students modify pollution thresholds through programming and interpret the resulting measurements. These integrated activities particularly support (3) evaluation and (5) explanation, as students evaluate the obtained measurements and explain how the MQ-2 sensor, Arduino circuit, calibration process, and alarm threshold function in detecting air-pollution levels.

Figure 1. Student worksheet (LKM) on the topic of air pollution

After completing the practical activity, students proceed to the Data Processing section. In this activity, students identify variables, formulate hypotheses, complete the provided data tables, construct ISPU line graphs, and analyze the relationship between ISPU values and LED or buzzer activation. This activity integrates Science, Technology, Engineering, and Mathematics because students are required to process experimental data, interpret quantitative results, and relate sensor responses to air-pollution conditions. The activities strengthen (2) analysis and (4) inference by requiring students to identify relationships among variables, analyze patterns in the collected data, interpret ISPU values, and draw conclusions regarding increases or decreases in air-pollution levels based on the experimental results. The learning sequence continues with Practicum Results Evaluation, where students evaluate the effectiveness of the buzzer in relation to air-monitoring applications, determine an appropriate ISPU threshold for activating the alarm, and propose solutions based on the experimental data. This activity emphasizes the Technology and Engineering aspects of STEM because students evaluate the functionality and potential application of the developed air-pollution detection device. At this stage, students develop (3) evaluation by assessing the effectiveness of the device and the suitability of the alarm threshold, as well as (4) inference by drawing conclusions and proposing data-based solutions based on the experimental findings.

Finally, the LKM concludes with the Self-Regulation activity, in which students engage in critical reflection through five questions concerning the causes and effects of air pollutants, evaluation of the technology used, prediction of impacts, public outreach measures, and potential innovations using the Internet of Things (IoT) based on the laboratory results. This activity integrates Science, Technology, Engineering, and Mathematics and directly develops (6) self-regulation, as students reflect on their understanding, evaluate the results of their learning and experimentation, and consider possible improvements and innovations. Overall, the learning activities in the developed STEM-based Student Worksheet provide a coherent learning sequence that combines conceptual understanding, hands-on experimentation, data processing, evaluation, and reflection. Through these activities, the worksheet not only guides students in using an Arduino Uno and MQ – 2 sensor to detect air pollution but also provides structured opportunities to develop the six critical thinking indicators: interpretation, analysis, evaluation, inference, explanation, and self-regulation (Facione, 2015).

The results of the air pollution detection devices utilizing MQ – 2 sensors and Arduino, as provided in the LKM through the QR code, are presented in Figure 2.

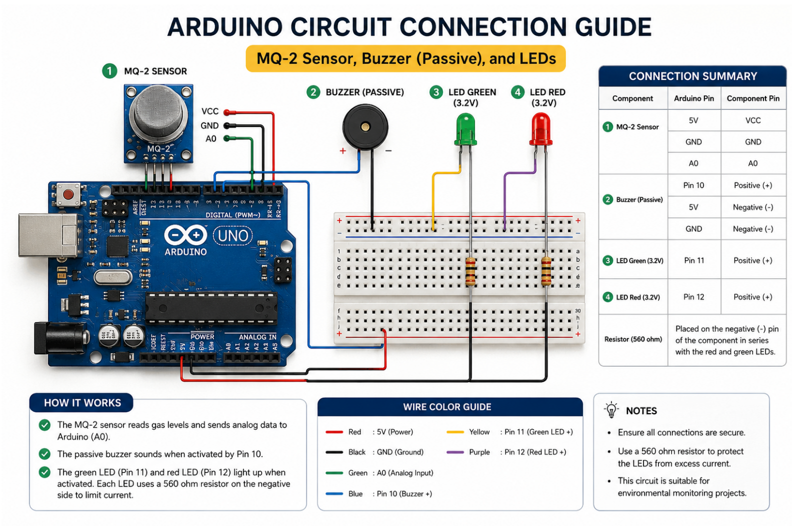

Figure 2. Arduino-uno design

A tutorial video, accessible through a QR code or YouTube link, is provided to guide students in assembling an air-pollution detection device using an Arduino and MQ-2 sensor. The LKM integrates all four STEM aspects. In the Science aspect, students learn about air pollution and the characteristics of polluted air. The Technology aspect involves assembling the air-pollution detection device, accessing the instructional videos provided in the LKM, and performing programming (coding) to operate the Arduino microcontroller according to the required functions.

In the Engineering aspect, students assemble the air-pollution detection device by installing the MQ-2 sensor, resistors, and LED indicators on the Arduino board, connecting the sensor circuit to the Arduino Uno using jumper cables, and connecting the Arduino Uno to a laptop via a USB cable. Meanwhile, the Mathematics aspect requires students to interpret air-pollution measurement results, calculate average pollution values, and determine the probability of air-pollution occurrence.

The reliability of the air-pollution measurement procedure was supported by a 6-minute sensor stabilization period before data collection. During this period, the MQ-2 sensor produced readings below 100, indicating that the sensor had reached the predetermined initial measurement condition. The measured data were subsequently interpreted using the ISPU classification provided in the worksheet, allowing students to relate numerical sensor readings to air-quality conditions. The classification ranged from Good (1–50), Moderate (51–100), Unhealthy (101–200), Very Unhealthy (201–300), to Hazardous (≥301). This procedure enabled students to use the sensor-generated measurements as contextual evidence for analyzing air-pollution conditions rather than treating the Arduino activity merely as a technical exercise.

The LKM was considered feasible based on the technical aspects of presentation, content, and language assessed through the validation sheet. The criteria included in each aspect provided the basis for evaluating the feasibility of the STEM-based LKM. The results of the validation of the STEM-based LKM conducted by the validators are presented in Table 4.

Table 4. Results of recapitulations of STEM-based student worksheet validation.

No	Aspects	Score
1.	Presentation Feasibility Aspects	86,11%
2.	Content eligibility aspect	97,91%
3.	Language qualification aspect	90%
4.	Aspects of suitability with the STEM approach	100%
	Average	93,50%
	Validation category	Highly valid

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The validity results for the STEM-based student worksheet—which utilized Arduino MQ-2 sensors and buzzers to measure air pollution—placed it in the "high validity" category across all evaluation criteria. The presentation component achieved an average score of 86.11%, reflecting the quality of the presentation, layout clarity, readability of instructions, and visual consistency, all of which contribute to the worksheet's usability. Students are better able to comprehend ideas logically and in context when presentations are clear and well organized (Yusuf & Widyaningsih, 2022). Although the presentation feasibility score was 86.11%, lower than the 100% score for STEM alignment, both components remained within the highly valid category. The difference suggests that the main area requiring further refinement was not the integration of STEM components, but the presentation of the worksheet, particularly aspects related to layout, visual organization, readability, and clarity of instructions. Meanwhile, the perfect score for STEM alignment indicates that the integration of science, technology, engineering, and mathematics was considered appropriate and consistently represented in the learning activities. Therefore, revisions to the worksheet were primarily directed toward improving its visual and instructional presentation while maintaining the existing STEM structure and Arduino MQ-2 activities.

The average score for the content feasibility component is 97.91%. This score takes into account the content's relevance to critical thinking indicators, the appropriateness of air pollution concepts, the integration of STEM elements, and the content's alignment with the learning objectives. The validity of STEM-based tools and worksheet is typically established through validator assessments of content feasibility, language feasibility, and presentation feasibility. The content feasibility aspect assesses the material's conceptual appropriateness and suitability with the learning objectives, as well as the importance of the activities on the worksheet (Widiarti et al., 2022). With an average score of 90%, the language feasibility component was deemed "highly valid." In addition to fostering critical thinking and scientific reflection, communication, grammatical accuracy, spelling, appropriate use of scientific terminology, and clear instructions helped students comprehend experimental procedures and interpret environmental data(Yusuf & Widyaningsih, 2022). STEM integration in educational activities was indicated by the maximum score of 100% on the STEM alignment component. To enable students to comprehend environmental issues in context and systematically, STEM integration is reflected through the use of sensor technology, measurement procedure design, and quantitative data analysis. As a result, STEM alignment in teaching materials must guarantee the overall integration of these elements in learning activities (Nugraha et al., 2024). Overall, the average validity of STEM-based Student Worksheet reached 93.50% with a category of highly valid, indicating that the Student Worksheet have met the criteria for teaching materials in terms of content, presentation, and language before being implemented in learning (Hikmah et al., 2023).

The practicality of the LKM was evaluated based on the implementation of learning activities and students' responses to the questionnaire. Combining student response questionnaires with observation sheets of learning implementation is commonly applied in the development of instructional materials, as questionnaires provide information about users' perceptions, while observation sheets document the actual implementation of the learning activities.

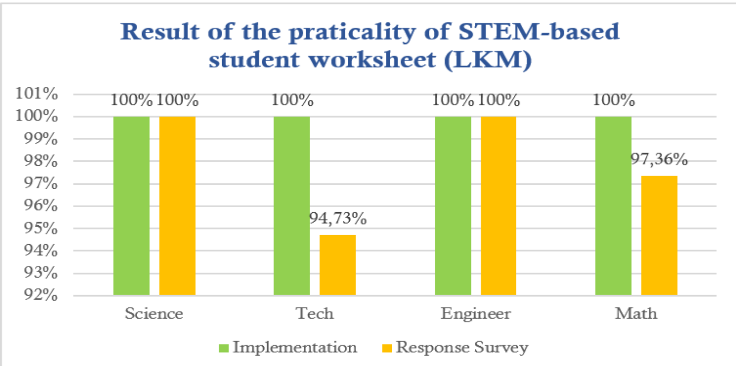

Figure 3. Graph of the practical results of STEM-based worksheet (LKM)

Figure 3 presents the results of the activity implementation and student response questionnaire. The implementation of the STEM-based Student Worksheet was assessed independently by six observers. All six observers obtained identical scores, resulting in an implementation score of 100% for each STEM component, including Science, Technology, Engineering, and Mathematics. The identical scores across the six observers indicate complete agreement in the observation of the learning activities and provide strong descriptive evidence that all planned STEM activities were implemented consistently during the learning process.The student response results were also highly positive, with 100% for Science, 94.73% for Technology, 100% for Engineering, and 97.36% for Mathematics. Although the Technology aspect obtained the lowest response score (94.73%), the result remains very high and indicates that students responded positively to the use of Arduino MQ-2 technology in the learning activities. Overall, these findings demonstrate that the STEM-based Student Worksheet was practical and well received by students, particularly because the activities provided direct experience in applying STEM concepts through air-pollution detection. This finding is supported by STEM-based teaching research reporting a validity score of 3.65 (very valid), student response rates of 95–97%, and appropriate readability, indicating that systematically designed STEM teaching materials can effectively support the achievement of learning objectives (Mahmudi et al., 2020).

Table 5. Recapitulation of N-Gain pretest and posttest results for critical thingking skills.

Details of the Question	**Science literacy indicators**	**Pretest**	**Posttest**	**N-gain**	**Category**
1 & 2	Interpretation – Understanding and assigning meaning to information, situations, or data.	68,42	96,05	0,88	High
3, 4, & 5	Analysis – Identifying relationships among ideas, statements, concepts, or representations.	41,05	89,87	0,83	High
6, 7, & 8	Explanation – Providing evidence-based reasoning and expressing it through rational arguments.	92,94	98,20	0,75	High
9 & 10	Inference – Drawing conclusions based on available evidence and reasons.	85,22	97,17	0,81	High
11 & 12	Evaluation – Assessing the validity of statements and the strength of logical relationships.	72,70	99,01	0,96	High
13 & 14	Self-Regulation – Reflecting on and correcting one's own thinking process.	66,67	95,61	0,87	High
Average		70,16	95,76	0,85	High

The average N-Gain result of the pretest and posttest based on the six critical thinking indicators was 0.85, which is classified as high. The improvement was observed across all indicators, namely interpretation (0.88), analysis (0.83), explanation (0.75), inference (0.81), evaluation (0.96), and self-regulation (0.87). These findings indicate that the STEM-based Arduino MQ-2 Student Worksheet was effective in improving students' critical thinking skills through activities involving air-pollution concepts, Arduino-based experiments, data processing, evaluation of practicum results, and reflection. The highest N-Gain was obtained for the evaluation indicator (0.96), which may be attributed to the characteristics of the learning activities provided in the worksheet. The STEM-based activities required students to examine the air-pollution data generated by the Arduino MQ-2 sensor, compare the measured results with relevant air-quality information, and assess whether the experimental findings supported the statements and conclusions presented in the worksheet. Students were also guided to evaluate the results of the practicum by identifying the consistency between the observed data, scientific concepts, and the proposed explanations. These tasks directly required students to judge the strength and relevance of evidence before determining an appropriate conclusion. The repeated involvement of students in

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interpreting authentic measurement data and evaluating evidence may have provided greater opportunities to practice the evaluation indicator than the other critical-thinking indicators. This finding suggests that integrating real-time sensor data with structured STEM inquiry activities can particularly support students' ability to evaluate evidence and make evidence-based judgments (Khotimah et al., 2023).

The explanation indicator showed the lowest N-Gain of 0.75, although it remained in the high category. This indicator increased from a pretest score of 92.94 to a posttest score of 98.20, suggesting that the relatively lower N-Gain was associated with students' already high initial ability, which limited the room for further improvement. In contrast, the analysis indicator demonstrated the largest absolute increase among the six critical thinking indicators, rising from 41.05 to 89.87, or an increase of 48.82 points. This substantial improvement indicates that students initially experienced greater difficulty in processing and examining information, but developed a stronger ability to identify relationships, examine patterns, and organize evidence after engaging with the worksheet activities. The improvement can be attributed to activities that required students to process data generated by the Arduino MQ-2 sensor, compare measurements, identify patterns in air-pollution data, and relate the findings to relevant biological concepts. These activities provided repeated opportunities for students to transform raw experimental data into meaningful information and use it to support their reasoning. Thus, the substantial improvement in the analysis indicator suggests that the STEM-based Arduino MQ-2 Student Worksheet was particularly valuable in developing students' ability to process and analyze authentic experimental data. Meanwhile, the interpretation indicator increased from 68.42 to 96.05, further indicating that students became more capable of understanding and interpreting the results of their investigations. The discussion, practical activities, data processing, and evaluation tasks collectively encouraged students to investigate problems and use evidence to develop their critical thinking skills, consistent with previous findings that STEM-based learning promotes critical thinking through active problem-solving and investigation activities (Gusman et al., 2023).

Beyond the general pattern of improvement, the specific mechanism through which the STEM–Arduino MQ-2 integration appears to have supported students' critical thinking can be traced directly to the sequence of activities in the Student Worksheet. The discussion activities and essential concepts required students to interpret information about air pollution and analyze relationships among pollutants, while the practical activities allowed them to directly assemble and operate the Arduino Uno–MQ-2 detection device. The real-time measurements obtained from the sensor then provided students with authentic data to process, interpret, and evaluate rather than relying solely on information presented in the worksheet. These activities are reflected in the high N-Gain results across all six critical thinking indicators, namely interpretation (0.88), analysis (0.83), explanation (0.75), inference (0.81), evaluation (0.96), and self-regulation (0.87), with an overall N-Gain of 0.85 in the high category. The highest improvement in evaluation indicates that the activities requiring students to assess the effectiveness of the device, determine appropriate ISPU thresholds, and formulate solutions based on experimental results provided strong opportunities to evaluate evidence and logical relationships. STEM learning that combines hands-on investigation, technology, and problem-solving activities has similarly been shown to support the development of multiple critical thinking indicators, including interpretation, analysis, evaluation, inference, explanation, and self-regulation (Bahtiar et al., 2024).

The practicality results likewise demonstrate that the STEM components were successfully implemented throughout the learning process, with 100% implementation for Science, Technology, Engineering, and Mathematics. Student responses were also highly positive, reaching 100% for Science, 94.73% for Technology, 100% for Engineering, and 97.36% for Mathematics. The slightly lower response to the Technology aspect (94.73%) compared with the other STEM components suggests that students' responses to the technology-related activities were relatively less favorable, although they remained within the very high category. However, the available response data do not directly identify the specific factors underlying this difference. Therefore, the lower Technology score should not be attributed specifically to difficulties in Arduino programming or device operation without additional evidence from student feedback or observation data. Nevertheless, the high response score indicates that students were able to engage positively with the Arduino-based learning activities. The slightly lower response to the Technology aspect indicates that the Arduino programming and device-operation activities may have required greater effort from students than the other STEM components; however, the response remained very high, showing that students were able to engage positively with the technology-based activities. This pattern is consistent with the N-Gain results, particularly the high improvement in analysis (0.83), evaluation (0.96), and self-regulation (0.87), which were supported by activities involving sensor operation, data processing, evaluation of the detection device, and reflection. These results suggest that the Arduino-based activities provided opportunities for students to work with experimental data and evidence, although the present data do not establish a direct causal relationship between the Technology response score and the improvement in specific critical-thinking indicators (Annisa et al., 2024).

These findings indicate that integrating a low-cost, real-time air-pollution detection device into a structured STEM-based Student Worksheet provides Biology Education students with authentic, data-driven learning experiences that can support the development of critical thinking skills. The Arduino Uno and MQ-2 sensor activities allow students to directly engage with air-pollution phenomena, process experimental data, evaluate the performance of the detection device, draw conclusions, and reflect on their learning. Therefore, instructors implementing similar Arduino-based STEM worksheets should combine the technological activities with clear technical guidance, particularly for programming and circuit assembly, while also providing sufficient opportunities for students to analyze data, evaluate evidence, formulate conclusions, and reflect on their own thinking processes. Although the developed STEM-based Student Worksheet demonstrated high practicality and a high level of improvement in students' critical thinking skills, several limitations should be considered. First, the product was evaluated through a limited trial involving only 38 Biology Education students from a single university, which limits the generalizability of the findings to broader educational contexts. Second, the developed worksheet focused specifically on the air pollution topic; therefore, its application to other Biology topics has not yet been examined. Third, the effectiveness of the worksheet was evaluated using a one-group pretest–posttest design without a control group, making it difficult to determine whether the observed improvement was solely attributable to the developed worksheet. Fourth, the pretest-posttest instrument was not subjected to empirical validity and reliability testing before being used to assess the improvement in students' critical thinking skills. Although the instrument was reviewed by expert validators for content alignment, the absence of empirical item-level validity and reliability evidence limits the strength of the measurement conclusions. Therefore, future research is recommended to (1) provide more comprehensive technical guidance for Arduino programming and circuit assembly, (2) expand the implementation to larger and more diverse groups of students and institutions, (3) apply the STEM-based worksheet to other Biology topics, (4) employ experimental or quasi-experimental designs involving control groups to obtain stronger evidence regarding its effectiveness in improving students' critical thinking skills, and (5) conduct empirical validity and reliability testing of the critical-thinking pretest-posttest instrument before its wider implementation.

Conclusions

The STEM-based Student Worksheet using Arduino Uno and the MQ-2 sensor on the topic of air pollution developed in this study demonstrated (average 93,50%) very high validity and practicality, with all STEM components achieving 100% implementation, while student responses reached 100% for Science, 94.73% for Technology, 100% for Engineering, and 97.36% for Mathematics. The effectiveness analysis also showed an average N-Gain of 0.85 (high) across the six critical thinking indicators, namely interpretation (0.88), analysis (0.83), explanation (0.75), inference (0.81), evaluation (0.96), and self-regulation (0.87). The main contribution of the worksheet lies in integrating authentic, real-time air-pollution data generated by the MQ-2 sensor into structured STEM learning activities. Through these activities, students were able to collect and process environmental data, interpret experimental results, evaluate evidence, formulate conclusions, and reflect on their reasoning. Thus, the Arduino MQ-2 was positioned not merely as a technological teaching aid, but as an authentic data source embedded within the learning process to support the development of students' critical thinking skills. Within the scope of the one-group pretest-posttest trial involving 38 Biology Education students at Universitas Negeri Surabaya, the developed worksheet represents a promising instructional alternative for contextualizing STEM learning and supporting critical thinking in air-pollution learning. Further research should prioritize controlled experimental or quasi-experimental designs involving larger and more diverse samples, together with empirically validated and reliable critical-thinking instruments, to provide stronger evidence of the effectiveness of Arduino-integrated STEM learning.

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