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Arduino-based STEM student worksheet to improve scientific literacy in air pollution learning

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ABSTRACT

Scientific literacy is a crucial competency for Biology Education students to understand scientific concepts and address environmental issues. However, Indonesian students' scientific literacy remains relatively low, indicating the need for innovative learning resources. This study aimed to develop and examine the validity, practicality, and effectiveness of an Arduino Uno-assisted STEM-based student worksheet on air pollution to improve scientific literacy. Using the Four-D (4D) model (define, design, develop, and disseminate), the worksheet was validated by two expert validators and tested on 36 Biology Education students. Data were collected through validation sheets, student response questionnaires, learning implementation observations, and pretest-posttest tests, then analyzed using validity percentages, practicality scores, and N-gain. The worksheet achieved a validity score of 91% (highly valid), practicality scores of 97.30–100% (very practical), and an average N-gain of 0.80 (high). Within the scope of this one-group pretest-posttest trial, these results indicate that the developed worksheet is valid, practical, and shows a promising initial effect for enhancing Biology Education students' scientific literacy.

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Introduction

Scientific literacy stands out as an essential skill that everyone should possess, as it is closely linked to understanding the environment and the scientific and technological issues facing modern society (Guerrero & Sjöström, 2025). Efficient instruction in science significantly contributes to improving scientific understanding, especially at the university level. Following the PISA scientific literacy framework, scientific literacy is conceptualized as the competence to explain phenomena scientifically, to construct and evaluate designs for scientific inquiry, and to interpret data and evidence scientifically in order to engage as a reflective citizen with science-related issues (OECD, 2019). These competencies encompass both the comprehension of scientific ideas and the capability to utilize scientific approaches to address practical issues. Students need to have these science literacy skills so that they not only understand science as a concept, but also assist learners in understanding scientific ideas as well as utilizing them in daily life scenarios (Astuti et al., 2025).

In Indonesia, scientific literacy is still comparatively low, as seen from the results of PISA research from 2000 to 2019, which placed Indonesia as one of the countries with low science competency (Fiyantara et al., 2025). PISA evaluates student competencies in reading, mathematics, and science, and Indonesia has consistently scored below the OECD average since its first participation. According to the most recent cycle, Indonesia's scientific literacy score is 396, ranking 73rd out of 79 participating countries (OECD, 2023). Although PISA specifically assesses 15-year-old school students, this pattern remains relevant to the present study because Biology Education students entering university have generally been educated within the same national system, and scientific literacy gaps formed at the secondary level tend to persist into higher education unless addressed through targeted instructional interventions (Guerrero & Sjöström, 2025) Insufficient scientific literacy hampers students understanding of the scientific principles they need to comprehend to value the continous learning experience. This results in prolonged learning that amounts to little more than rote memorization (Utami et al., 2022). According to the PISA evaluation, Indonesian students' scientific literacy needs immediate attention because their scores are still below the global average.

The method of learning through STEM contributes beneficially to the enhancement of scientific literacy. In general, STEM-based learning increase students to develop, utilize, design, and apply science and technology and can also enhance conceptual understanding through structured hands-on experiences (Ardian et al., 2024; Prihatiningtyas et al., 2025). Logical reasoning, critical thinking, literacy, and higher-order thinking skills can all be developed through STEM-based learning, which combines the four disciplines of science, technology, engineering, and mathematics into a unified educational experience (Agussuryani et al., 2022; Khairuna, 2023). STEM-based learning can also prepare students to adapt better to international changes and enhance their utilization of technology (Artobatama et al., 2023). The topic of air pollution is highly relevant in STEM-based learning because it allows students to understand real environmental issues and develop practical skills using technology (Maspul, 2024). STEM learning that uses Arduino devices as a platform for measuring air quality provides an interactive and practical learning experience by assembling and operating air sensors to detect air quality indices. An Arduino Uno microcontroller paired with an MQ-2 gas sensor was selected for this purpose because it is low-cost, open-source, and readily programmable, which makes it accessible for classroom-scale STEM instruction while still providing sufficiently sensitive, real-time gas-concentration readings for inquiry-based air-quality measurement (Ga et al., 2021; Ga & Chang, 2025) Students can take direct measurements in their surrounding environment and analyze the measurement data in real time.

This sequence of activities is deliberately aligned with the scientific literacy competencies targeted in this study: assembling and operating the sensor circuit requires students to explain the phenomenon of air pollution scientifically, recording and troubleshooting the measurement procedure engages the competency of evaluating and designing scientific investigation, and analyzing the resulting concentration data engages the competency of interpreting scientific data and evidence to make decisions. In the context of scientific literacy, this task enhances learners' skills in gathering, examining, and making inferences from scientific information, which are important skills for 21st-century science learning (Oh, 2025). In addition to enhancing cognitive scientific literacy, the issue of air pollution in STEM education gives students useful skills and a sense of environmental social responsibility. This approach aligns with the purpose of education is to generate graduates who are prepared to address global challenges with relevant knowledge and competencies, as well as an awareness of the importance of environmental sustainability (Kraft et al., 2025). Studies have been carried out on creating worksheets focused on STEM to enhance students' understanding of science. Learning that focuses on STEM can also prepare students to adapt better to international changes and enhance their utilization of technology (Sulistiyowati et al., 2018).

Earlier studies have demonstrated that worksheets focused on STEM topics can significantly enhance students' abilities in scientific literacy. Several recent studies have introduced Arduino-based STEM activities in biology education, reporting gains in conceptual understanding, computational thinking, and practical measurement skills (Görgülü Arı & Meço, 2021; Nawawi & Dafrita, 2022) Although these studies demonstrate a high degree of suitability of Arduino-based tools for biology instruction, their focus has remained primarily on hardware development, validity, and practicality, without embedding the technology within a structured worksheet explicitly designed to foster the specific competencies of scientific literacy. In a related but separate line of research, digital and problem-based-learning worksheets have been developed specifically on environmental topics: a STEM-based electronic worksheet was validated to improve scientific literacy on environmental change material, and a problem-based-learning electronic worksheet was developed on air pollution material to encourage active learning (Destiansari et al., 2024; Fitria et al., 2025). However, these worksheet-based studies relied on digital media without a physical measurement device and did not integrate real-time environmental data collection into the STEM worksheet activities.

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Therefore, an absence persists in the creation of student worksheets centered on STEM that incorporate Arduino Uno and MQ-2 sensors for inquiry-driven learning tasks, while also assessing how effectively they enhance scientific literacy in students studying Biology Education. The novelty of this study is threefold: (1) product novelty, in the form of a printed STEM student worksheet that structures air-pollution learning around the five scientific literacy competencies assessed in this study; (2) technological novelty, in the integration of an Arduino Uno and MQ-2 sensor circuit as a low-cost, real-time environmental monitoring tool embedded directly into the worksheet activities rather than presented as a standalone device; and (3) empirical novelty, in the joint examination of the validity, practicality, and effectiveness of this Arduino-integrated worksheet for improving Biology Education students' scientific literacy. Specifically, this study aims to (a) develop an Arduino Uno-assisted STEM student worksheet on air pollution and (b) examine its validity, practicality, and effectiveness for improving scientific literacy in students studying Biology Education. This study addresses the identified gap by developing an Arduino Uno-assisted STEM student worksheet on air pollution that combines hands-on experimentation, real-time environmental data collection, engineering design activities, and scientific literacy assessment.

Method

This study employed a Research and Development (R&D) method using the Four-D (4D) development model developed by Thiagarajan (1974),which consists of four stages: define, design, develop, and disseminate. The participants were 36 Biology Education students at Universitas Negeri Surabaya enrolled in a General Biology course, selected using a purposive sampling technique on the criterion that they had not previously completed the air-pollution detection practicum. The worksheet was validated by two expert validators (a media/instructional-design validator and a content/material validator) together with the supervising lecturer. The instrument used to assess validity and practicality was reviewed for content validity by the same expert validators prior to use, and its items were adapted from previously validated worksheet-assessment instruments to support its reliability.

Scientific literacy in this study was assessed using five indicators adapted from the PISA scientific literacy framework, namely (1) identifying scientific problems, (2) explaining phenomena scientifically, (3) designing and evaluating scientific investigations, (4) interpreting data and scientific evidence, and (5) using scientific evidence to make decisions (OECD, 2019) Three components of analysis are 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 concentrates on creating an initial product prototype. In this instance, the design process focused on creating a STEM-based student worksheet that included the ideas 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, and scientific literacy tasks. The Development phase is executed to produce a research output. The output in this research is a STEM-based student worksheet on air pollution material 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 36 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 tools utilized in this research included assessment forms, student feedback surveys, activity execution forms, and questions for pretests and posttests. The pretest-posttest instrument was designed to measure five scientific literacy indicators used consistently throughout this study: identifying scientific problems, explaining phenomena scientifically, developing and evaluating designs for scientific investigations, analyzing scientific evidence and quantitative data critically, and making decisions and taking action based on scientific information, adapted from the PISA scientific literacy framework (OECD, 2019). The viability, usefulness, and efficacy of a STEM-based student worksheet on air pollution will be assessed using quantitative analysis of the data collected from the instruments utilized. The statistical validity and reliability of the pretest-posttest instrument were not computed in this study; this is acknowledged as a methodological limitation. All quantitative data, including validity scores, practicality percentages, and N-gain values, were processed and calculated using Microsoft Excel

2021 to ensure accurate data tabulation and analysis. The validity sheet refers to the Likert scale to provide assessments on a scale of 1(Not valid), 2(A little bit valid), 3(Valid), 4(Highly valid) (Dika et al., 2025).

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

A practicality analysis was conducted by examining the results of implementation activities in the learning process and student responses to questionnaires. The Guttman scale was used for descriptive analysis of the response questionnaire, which included both positive and negative items. "Yes" was assigned a score of 1 and "No" a score of 0 (Sugiyono, 2022).

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 results of the students pretest and posttest were analyzed according to the established indicators and the assessment results will be interpreted based on the N-Gain criteria listed in Table 3. The N-Gain classification into high, moderate, and low categories follows the criteria established by Hake (1998). N-Gain analysis is performed to evaluate the enhancement realized compared to their highest possible improvement. N-Gain is extensively utilized in scientific education studies as considers variations in starting scores, offering more equitable assessment of teaching 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 limited product testing on 36 students majoring in Biology Education at Surabaya State University. The aim of creating this LKM was to enhance the scientific understanding of students pursuing a degree in Biology Education. This was subsequently accompanied by several research of the STEM oriented student worksheet that has been prepared can be observed in figure 1.

The outcomes of the LKM development are displayed in Figure 1. The LKM contains learning outcomes and objectives, which are sub-topics that must be achieved, short scientific readings on the fundamental ideas of air contamination to assist learners in comprehending the content related to air pollution the material on air pollution, explanations of the tools and materials, and the steps to be taken during experiments to detect air pollution using Arduino and MQ-2 sensors. There is a YouTube QR code that links to a tutorial video on air pollution detection tools by Arduino and MQ-2 sensors, as well as a table to be completed with the results of the experiments conducted.

The learning activities in the Student Worksheet (LKM) that was developed are systematically integrated using the STEM approach framework, aligned with the PISA science literacy components. The activities begin with the Empathize & Assessment stage, where students are presented with an authentic local issue regarding the phenomenon of surging air pollution through scientific articles and air quality classification tables based on ISPU values, along with several questions derived from the scientific articles. This stage addresses the Science aspect while fostering PISA competencies in identifying scientific problems and explaining phenomena scientifically. Next, during the Research & Ideation phase, students were encouraged to conduct group investigations to plan real-world solutions for measuring air quality. In this phase, the Technology aspect was integrated through an introduction to the Arduino Uno microcontroller and gas sensors, which served to equip students with procedural knowledge regarding how technological instruments work in detecting pollutant particles. The next module focuses on practical and engineering aspects through the Prototype/Engineering Design phase. In this phase, students engage in engineering activities by following the circuit diagrams provided in the learning materials to assemble hardware components, connect gas sensors, and write lines of code in the Arduino IDE software. These activities directly develop students' PISA competencies in evaluating and designing scientific investigations, including the ability to troubleshoot technical errors.

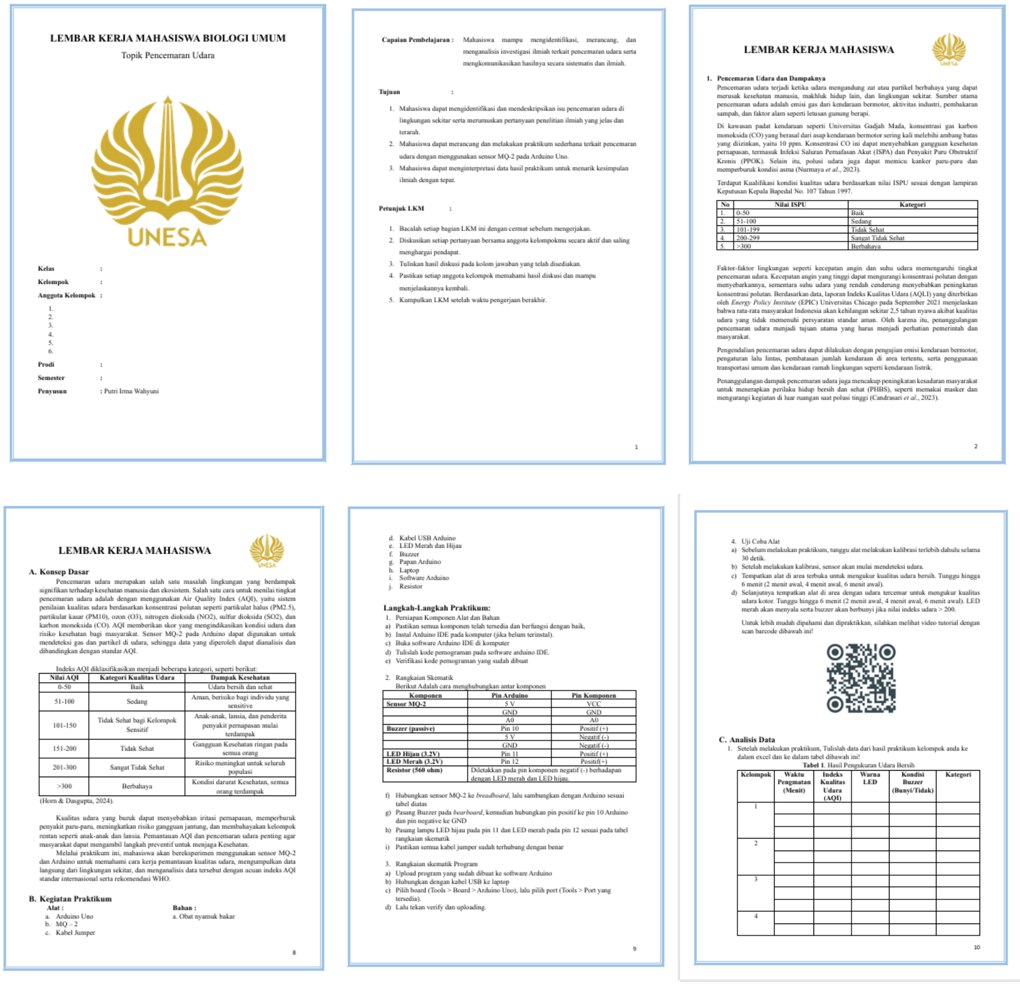

Figure 1. Student worksheet (LKM) on the topic of air pollution

After the devices were successfully assembled, the activity moved on to the Testing & Data Collection phase, which integrated mathematical concepts. Students collected real-time data on pollutant levels at various locations across the campus, then presented the data in tables and graphs. This mathematical activity directly contributed to strengthening PISA competencies in critically interpreting data and scientific evidence. The learning sequence in this LKM concludes with the Evaluation & Reflection phase, during which students analyze the results of the graphs and relate them to scientific arguments supporting their conclusions, while also reflecting on concrete actions that can be taken to reduce pollution. This directly supports the strengthening of PISA competencies in using scientific information for decision-making and action. With this coherent structure of STEM activities, the LKM serves not only as a guide for technology labs but also as a strategic tool for comprehensively improving students' science literacy.

The results from a series of air pollution detection devices, using MQ-2 sensors and an Arduino, located at LKM, as accessed via QR code, are shown in Figure 2.

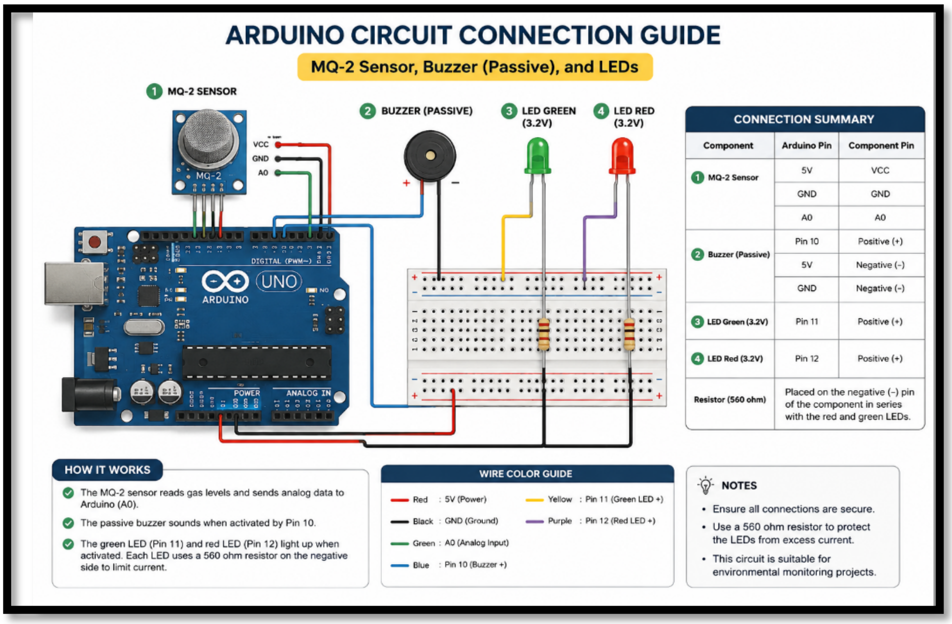

Figure 2. Arduino-uno design

Video tutorial via QR code or YouTube on assembling an air-pollution detection device by Arduino and MQ-2 sensors. This LKM covers all aspects of STEM; in the science domain, students learn about air pollution and the characteristics of polluted air. In the technology aspect, students can assemble an air pollution detection device, access the videos provided in the LKM, and perform programming (coding) to give commands to the Arduino microcontroller so that it can perform its functions.

Engineering students can assemble air pollution detection devices such as installing MQ-2 sensors, resistors, and LED lights on an Arduino board, connecting the electrical current from the Arduino Uno to the sensor circuit via jumper cables, and connecting the Arduino Uno to a laptop via a USB cable. Finally, in mathematics, students can read air pollution measurement results, calculate average pollution values, and calculate the probability of air pollution occurring.

LKM can be considered feasible in terms of the technical aspects of presentation, content, and language listed in the validation sheet. Various criteria listed in each of these aspects support the validation assessment of STEM-based LKM. The results of STEM-based LKM validation by validators are shown in Table 4.

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

No	Aspects	Score
1.	Presentation Feasibility Aspects	81,25%
2.	Content eligibility aspect	97,72%
3.	Language qualification aspect	85%
4.	Aspects of suitability with the STEM approach	100%
	Average	91%
	Validation category	Highly valid

The presentation's feasibility aspect received a score of 81.25%. The influence of visual design on students' interest in learning including elements such as color and typography affects their focus, motivation, and engagement in learning; therefore, these aspects are important in assessing the validity of instructional material presentation (Rizky & Marssellina, 2025). Furthermore, the content feasibility aspect scored 97.72%. The activities presented in the LKM not only conveyed theory but also linked it to real phenomena, so that students could connect scientific concepts to everyday contexts (Saefullah & Rostikawati, 2024). The Language component earned a rating of 85% for both systematic and communicative language use helps improve readability and minimize ambiguity in learning instructions, enabling students to follow learning activities more clearly and easily (Sudiati, 2023).

The STEM Suitability aspect scored 100%, firstly in science, The STEM Alignment aspect received a score of 100%. The assessment indicators within this aspect include four components: (1) the LKM helps students understand the concept of air pollution through direct scientific observations and experiments; (2) the LKM facilitates the use of digital technology to automatically measure experimental data, display results in real time, and connect the biology learning process with technological advancements; (3) The LKM trains students to systematically design, assemble, and apply Arduino-based experimental tools to solve problems that arise during lab activities, (4) The LKM guides students to process sensor measurement results into numerical values, tables, and graphs, and to solve problems involving probability to enhance their quantitative skills. Each of these aspects received a perfect validation score of 4.

In the field of science, an understanding of air pollution concepts was developed through experiments and research conducted Tyas et al. (2020) the study showed that integrating experimental activities into worksheets can improve students understanding of scientific concepts while also developing their science process skills. Second, regarding real-time Arduino technology, research on the creation of STEM educational tools utilizing Arduino in practical experiments shows that the application of Arduino-based sensor devices can increase student engagement in the real-time data collection process and also improve scientific concept understanding (Oh, 2025). Thirdly, regarding engineering with sensor assembly, this can help students understand the components in Arduino. Finally, regarding mathematics with data processing, according to research Just & Siller (2022), STEM-based learning emphasizes the use of mathematics not only as a calculation tool but also as an important component for systematically processing and analyzing experimental data. The final results of the LKM validity test showed a score of 91%, resulted in a highly valid category with minor revisions. The highly valid validation score percentage indicates that the content, language, construction, and design of the material are appropriate.

The practicality of LKM is evaluated through the outcomes of executed activities and surveys filled out by students. Measuring practicality by combining student response questionnaires with observation sheets on learning implementation is a procedure commonly used in teaching material development research, because questionnaires capture user perceptions while implementation sheets record the actual process in the classroom.

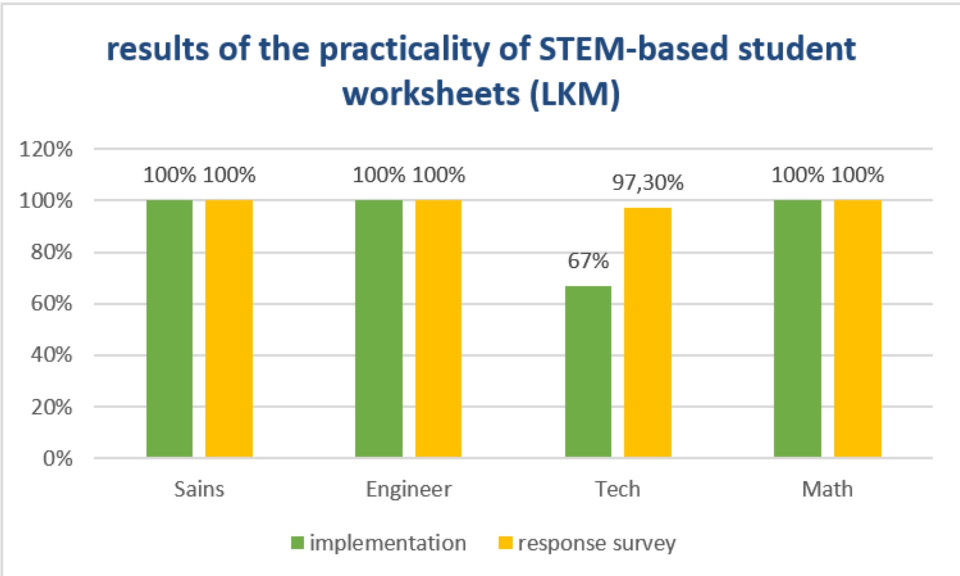

Figure 3. Graph of the practical results of STEM-based worksheet (LKM)

Figure 3 shows the results of the implementation of activities and surveys on student feedback, indicating that all STEM components, namely science, engineering, technology, and mathematics, had an implementation score of 100%, except for technology, which scored 67%. The student response questionnaire also scored 100%, except for the technology aspect, which scored 97.30%. The implementation score for the technology aspect is lower than the others, indicating that students may face a number of obstacles in implementing complex technological aspects in their LKM. However, the survey response rate was still relatively high at 97.30%, showing that learners remain eager to discover more about the available technology. The positive response from students shows their enthusiasm for using new technology in STEM-based learning (Anugrah et al., 2023). Meskipun demikian, skor implementasi teknologi sebesar 67% is the lowest among all STEM components and seems to contradict the common statement that all stages of STEM-based learning have been implemented very well. A closer look shows that this gap is largely caused by the programming and device assembly steps, which require students to configure the Arduino Uno-MQ-2 circuit and upload sketches on their own; these steps demand previous programming experience that most Biology Education students haven't had, so the implementation lags behind other STEM components even though students' interest in the technology remains high.

Table 5. Recapitulation of N-Gain pretest and posttest results for science literacy skills.

Details of the Question	Science literacy indicators	Pretest	Posttest	N-gain	Category
1,2 & 3	Identifying Scientific Problems	79,6	97,2	0,86	High
4, 5, 6, 11 & 12	Explaining Phenomena Scientifically	84	97,4	0,83	High
7, 13 & 14	Developing and evaluating designs for scientific investigations	64,3	87,1	0,63	Moderate
8, 9, 15	Analyzing scientific evidence and quantitative data critically	63	89,3	0,71	High
10	Making Decisions and Taking Action Based on Scientific Information	86	100	1	High
Average		75,38	94,2	0,8	High

The average results of the N-gain pretest and posttest recapitulation data based on 5 indicators of scientific literacy ability were 0.8, which is classified as high. Within the scope of this one-group pretest-posttest trial, this shows that STEM-based LKM with the topic of air pollution is effective for use. Several studies on scientific literacy based on the STEM approach have consistently revealed that this learning strategy can increase the overall N-gain score in scientific literacy indicators, showing that a learning approach that comprehensively combines science, technology, engineering, and mathematics has a significant positive impact on improving scientific literacy skills (Nilyani et al., 2023). Research shows that implementing a STEM approach can greatly enhance pupils' scientific literacy abilities. Studies using a pre-test–post-test design found an increase in scientific literacy scores following program implementation, proving that STEM learning strategies not only encourage active participation but also have a positive impact on overall scientific literacy skills (Usemahu et al., 2022).

The N-gain results pretest-posttest recapitulation on the indicators of designing and evaluating scientific investigation designs show moderate improvement, unlike other science literacy indicators. This can be explained by the fact that these indicators require higher-order thinking skills, such as formulating variables, developing procedures, and evaluating investigation designs (Eymur & Çetin, 2024). These skills cannot be developed instantly and require practice through continuous inquiry-based learning. Examining the structure of the investigation-related activities in this LKM, the experimental procedure and variables to be measured were largely pre-specified for students, and the worksheet provided a fixed data-recording table rather than asking students to independently propose their own investigation design; consequently, students had comparatively little opportunity to practice formulating variables or evaluating alternative procedures on their own, which plausibly explains why this indicator showed the smallest gain among the five. In addition, limited learning time and scaffolding in LKM mean that students' scope for exploration in designing investigations is not yet fully optimized, despite showing positive improvement.

Beyond the general pattern of improvement, the specific mechanism through which the Arduino-STEM integration appears to have driven these gains can be traced directly to the worksheet's activity sequence: hands-on assembly and operation of the Arduino Uno-MQ-2 circuit required students to engage concretely with the phenomenon of air pollution before they could explain it scientifically, while the real-time sensor readings gave students authentic quantitative data to analyze and use as the basis for decisions, rather than data supplied secondhand in a textbook. This direct link between physical measurement and literacy indicators plausibly explains why the largest gains occurred on the indicators most closely tied to hands-on data collection (identifying problems, explaining phenomena, and decision-making), while the smallest gain occurred on the indicator (designing and evaluating investigations) that the worksheet supported the least, as discussed above.

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The practicality scores likewise mirror this pattern at the level of individual STEM components: the near-perfect practicality of the science, engineering, and mathematics components corresponds with the high N-gain achieved on the indicators most dependent on those components (identifying problems, explaining phenomena, and interpreting data), whereas the comparatively lower technology-implementation score of 67% corresponds with the moderate N-gain on the investigation-design indicator, since both reflect the same underlying constraint of students' limited prior exposure to independent technical and procedural work. The STEM-based worksheets had a very positive response, according to the results of the student feedback form, especially in terms of interest, clarity of activity steps, and involvement in discussions and problem solving. In line with this, the results of the implementation of activities show that most stages of STEM-based learning could be carried out very well. This situation fosters the growth of scientific literacy by generating a purposeful process. The pretest and posttest results for scientific literacy show a jump in the high category across most parameters, with the exception of the designing-and-evaluating-investigations indicator discussed above, demonstrating the overall impact of this approach. The indicators of identifying problems and explaining scientific phenomena, as well as using scientific information for decision making, increased because students were accustomed to being faced with contextual problems (Wahono et al., 2025). Meanwhile, indicators for designing investigations and interpreting data improve through experimental activities and data analysis integrated into the STEM approach.

These findings suggest that integrating low-cost real-time measurement devices into structured STEM worksheets offers a practical way to provide Biology Education students with authentic, data-driven experiences that support most dimensions of scientific literacy, while also indicating that indicators requiring the design of independent investigations necessitate additional pedagogical support beyond what a single structured worksheet alone can provide. This implies that instructors adopting similar Arduino-based STEM worksheets should combine technological components with explicit technical guidance for example, a brief orientation on programming before the activity and intentionally provide opportunities for students to propose and justify their own research procedures, rather than following a fully predetermined protocol, if the goal is to strengthen research design competencies alongside other indicators of scientific literacy. Although these findings suggest that the developed STEM-based student worksheets are feasible, practical, and show promising initial effects, there are various limitations that need to be considered when analyzing the results. Despite the encouraging results, there are a number of issues with this study. First, the developed product was evaluated through a limited pilot study involving only 36 biology education students from a single university, thus limiting the ability to generalize the results to a broader educational context. Second, this study focused solely on the topic of air pollution; thus, the application of STEM-based student worksheets to other biology topics has not yet been investigated. Third, the worksheets' efficacy was evaluated using a one-group pretest–posttest methodology without a control group, which made it difficult to compare their efficacy with that of other teaching strategies. Therefore, future research is recommended to (1) strengthen the scaffolding for the investigation-design activities, for example by having students formulate their own measurement variables and procedures before consulting a model procedure; (2) provide brief introductory technology training so that the coding and circuit-assembly steps do not disproportionately lower the technology implementation score; and (3) implement the worksheets on a larger scale across various institutions, apply them to a variety of biological concepts, and use an experimental or quasi-experimental design with a control group to obtain more comprehensive evidence regarding their effectiveness.

Conclusions

The STEM-based student worksheet (LKM) using Arduino Uno on the topic of air pollution developed in this study achieved a validity score of 91% (highly valid), practicality scores ranging from 97.30% to 100% (very practical), and an average N-gain of 0.80 (high) across the five scientific literacy indicators assessed. Within the scope of this one-group pretest-posttest trial involving 36 Biology Education students, these results indicate that the developed LKM is valid, practical, and shows a promising initial effect for enhancing students' scientific literacy skills. The developed LKM is capable of systematically integrating aspects of science, technology, engineering, and mathematics through technology-based experimental and environmental data analysis activities. The application of this STEM-based LKM offers a relevant and significant educational experience, thereby supporting students' development of understanding of scientific concepts, interpretation of data, and decision-making based on scientific evidence. Thus, this STEM-based LKM can be considered a promising teaching alternative for biology learning on the topic of air pollution, pending further validation through larger-scale, controlled studies.

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