

Designing a Teaching-Learning Sequence for an Air Quality Measuring Project: a Qualitative Content Analysis for Interdisciplinary Learning

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Abstract

Keywords:
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Air pollution poses serious environmental and health concern, so innovative educational strategies are needed to make students aware and propose active solutions. This study aimed at developing a Teaching-Learning Sequence (TLS) in teaching air pollution for high school students, through the interdisciplinary project-based learning (PjBL). The data for the TLS development were from three key sources: journal articles, proceedings articles, and book chapters collected from Scopus database. Analysis technique was using the Qualitative Content Analysis (QCA) through the processes of identifying meaning units, coding, categorizing, and synthesizing the findings into the TLS framework. The resulting TLS was arranged into four quadrants: (A) causes and impacts of air pollution, (B) pollutants and their measurement technologies, (C) device construction with wireless communication, and (D) connections to Sustainable Development Goals (SDGs). The proposed TLS is intended to nurture the development of 21st-century skills, including problem-solving, critical thinking, creativity, collaboration, and environmental awareness, as well as promoting students' understanding of SDGs related to health, climate action, and sustainable cities. Three experts have been validated the TLS's relevance to the high school curriculum, suitability of its learning design, and ease of implementation, while also providing meaningful suggestions for improvement. This study advances innovative environmental education and essential sustainability skills.

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Introduction

Air quality is a critical metric for evaluating the condition of air in a specific region. Degradation in air quality, especially the ambient air, presents very significant threats both to human health and the general environment. Some of the key pollutants, like CO, dust, nitrogen oxides, and lead (Pb), have a direct link to respiratory and cardiovascular diseases besides causing environmental degradation (Zamorategui-Molina et al., 2021). In Indonesia, particulate pollution has increased sharply during the past decade, and currently over 93% of its population live in an area with a PM_{2.5} concentration surpassing the guideline thresholds recommended by the WHO (Arisanti et al., 2024). These pollutants have become such a serious health hazard that the life expectancy of people has reduced by an average of 2.5 years in the entire country and up to 5.5 years in Jakarta (Lee & Greenstone, 2021).

The widespread effects of air pollution underscore its significant influence on health outcomes. Addressing this issue requires more than scientific or technical solutions; it necessitates changes in societal norms and behaviors. Education is critical in generating such

awareness, leading people to become involved and take active part in the realization of that change. In respect to environmental issues concerning global interconnectedness, learning that synthesizes approaches and knowledge of many fields, particularly in interdisciplinary and transdisciplinary studies, bears importance (Shutaleva, 2023). By synthesizing perspectives and methodologies from various disciplines, interdisciplinary approaches promote the development of holistic and sustainable solutions. This framework encourages interconnected thinking and equips learners to address environmental issues with a broader and more integrated perspective (Yanniris, 2021).

Although the interdisciplinary approach in education is highly recognized for its ultimate potential with regard to complex environmental problems, many challenges still exist in the implementation of this method. Inflexible academic structures and rigidly defined subject areas are among the major obstacles to its implementation; such traditional structures often resist the adoption of truly holistic approaches to knowledge (Yanniris, 2021). Most of the time, teachers have to bear a lack of clear guidelines, resources, and training in such cases, which do not prepare them for the complexity of interdisciplinary teaching (Shutaleva, 2023). In addition, the lack of institutional support further heightens the challenges related to integrating interdisciplinary approaches into already existing curricula (MacLeod et al., 2023; Shutaleva, 2023).

Incorporating experiential and context-based learning has shown promising avenues for overcoming these barriers. For example, outdoor experiential learning has been reported to significantly improve students' environmental behavior with developed connections to their local environments (Yanniris, 2021). Similarly, PjBL is one useful framework through which environmental issues are to be tackled, knowledge from multiple disciplines is integrated, and important competencies are developed. Several studies have shown that PjBL not only enhances the problem-solving capacity of students but also fosters motivation, teamwork, and deeper understanding of environmental challenges (Stokes & Harmer, 2018). Most successful PjBL initiatives involve interdisciplinary collaboration, which helps students understand the interrelation of environmental issues and develop holistic solutions (MacLeod et al., 2023; Stokes & Harmer, 2018).

However, while the effectiveness of PjBL in general environmental education is well documented, its application to more specific topics, such as air pollution, remains understudied, especially at the high school level (Paek, 2018). Research tends to focus on pre-service teachers, which leaves a gap in how high school students, at such a critical stage of cognitive and career development, might benefit from interdisciplinary PjBL approaches that are specifically tailored to air pollution teaching and learning (Mandrikas et al., 2017; Rico et al., 2021).

Similar work in this regard has been attempted with the use of TLS, providing structured frameworks to present complex educational content in relation to air pollution. A more recent example of such a TLS is implemented in Greece using real-time meteorological data to teach about the relationship between air pollution, wind, and topography, showing positive learning outcomes related to conceptual understanding (Mandrikas et al., 2017). Another study designed an interdisciplinary TLS for pre-service primary teachers, integrating sustainability, mathematics, and science through constructivist and active learning strategies (Rico et al., 2021). Though these studies show the potential of TLS in improving understanding and

attitudes, they are targeting mainly pre-service teachers, thus leaving the needs of senior high school students largely unaddressed.

Moreover, the integration of technology in educational frameworks like TLS shows considerable potential to enhance learning outcomes. For instance, Geographic Information Systems (GIS) and real-time monitoring tools have been shown to improve higher-order cognitive skills, such as application and analysis, in air pollution learning (Cleary et al., 2017). Active learning strategies further enhance engagement and comprehension in environmental courses (Maipas et al., 2021). However, these technologies have hardly been applied to interdisciplinary PjBL at the high school level. Thus, presents an opportunity to explore the ways in which such innovations could support interdisciplinary learning and foster 21st century skills. Therefore, there is a need for a structured and feasible TLS that can support interdisciplinary environmental learning while engaging students in authentic technology-based projects.

These gaps are attempted to be filled with this current study by developing a TLS of PjBL in teaching the topic of air pollution in high school. Therefore, it provides an inclusive teaching-learning guide that will be able to enrich students' cognitive and practical knowledge related to air pollution and develop their critical thinking, problem-solving skills, environmental awareness, as well as promoting students' understanding of SDGs related to health, climate action, and sustainable cities. The research question then becomes how the content and design of a TLS can be developed to support interdisciplinary PjBL on the topic of air pollution. The unit of analysis in this study consists of interdisciplinary learning contents, project activities, and technological components related to air pollution education.

Method

To create a TLS based on an interdisciplinary PjBL approach, this work uses a Qualitative Content Analysis (QCA) technique. The project's main goal is to provide a tool for measuring air quality in relation to air pollution. The study's methodology is derived from Lindgren et al., 2020)'s systematic QCA framework, which highlights the de-contextualization and re-contextualization procedures for analyzing qualitative data. This method guarantees a strong analytical basis for creating an interdisciplinary TLS that incorporates technology use, experiential learning, and PjBL.

The TLS was developed via a systematic process that included the following steps:

1. **Data Collection:** Relevant data sources related to designing device to measure air pollution level as a project for students of senior high school, gathered from Scopus database. These sources included data from three key sources: journal articles, proceedings articles, and book chapters.
2. **Identification of Meaning Units:** Textual data were divided into specific meaning units, such as "types of air pollutants," "sensors for measuring air pollution," "sensor calibration techniques," and "PjBL approaches for air pollution topics."
3. **Condensation and Coding:** Meaning units were condensed to retain their essence and coded descriptively to reflect teaching-learning practices.
4. **Categorization:** Coded data were grouped into broader categories aligned with the study's purpose. The primary categories emerged: "project design," focusing on the technical

aspects of device development; “use of technology,” emphasizing the integration of digital tools and IoT components.

5. **TLS Framework Design:** The categories were synthesized into a step-by-step framework for implementing the TLS, incorporating designing device and measuring air quality as a central activity.

The proposed TLS framework emphasizes the construction and application of air quality measuring devices within school environments, enabling students to engage in authentic, context-specific learning experiences. This design leverages the findings of previous studies that highlight the effectiveness of PjBL and experiential learning in fostering 21st-century skills, such as critical thinking, problem-solving, and technological literacy. By integrating these elements, the TLS aims to enhance both cognitive and affective learning outcomes, providing students with meaningful opportunities to connect theoretical knowledge with practical environmental challenges.

The developed TLS was then qualitatively validated by three experts with relevant expertise in science education and interdisciplinary learning. The experts evaluated several aspects, including the relevance and suitability of the TLS content with the senior high school science curriculum, the learning design embedded in the TLS, its usability and feasibility for classroom implementation, as well as general suggestions for improvement. The feedback obtained from this expert validation process was subsequently used to revise and refine the TLS design before finalization.

Results and Discussion

Data Collection

The first stage of the Qualitative Content Analysis (QCA) involved collecting and reviewing literature related to the development and integration of air quality monitoring instruments with real-time mobile-based monitoring systems. Data were gathered from three primary academic sources: peer-reviewed journal articles, conference proceedings, and scholarly book chapters. These sources were selected to provide comprehensive insights into sensor technologies, mobile applications, data transmission systems, and environmental monitoring frameworks. The collected literature was systematically analyzed to identify key concepts, technological advancements, implementation approaches, and emerging trends. This process established a strong foundation for understanding current developments and guiding subsequent stages of the research. The journal articles will delve deep into the technical and scientific insights of air quality monitoring, whereas the proceeding articles present the state of practice and emerging technologies in the field. The chapters will provide comprehensive discussions of theoretical frameworks and inter/multidisciplinary perspectives related to air quality education. These were organized by using a coding system: Journal and proceeding articles were labeled as “A”, while book chapters were labeled as “B”; examples include “A1” for the first journal/proceeding article, “A2” for the second journal/proceeding article, etc., “B1” for the first book. The data collected are summarized below in Table 1, which has been coded systematically.

Table 1. The Collected Materials

No.	Author	Title	Code
1	Baldelli (2021)	Evaluation of a low-cost multi-channel monitor for indoor air quality through a novel, low-cost, and reproducible platform	A1
2	Bloss (2019)	Measurement of air pollutants	B1
3	Maring et al. (2023)	Airborne Particulate Matter and Associated Heavy Metals: A Review	A2
4	Valíček et al. (2012)	Emission distribution and regulation of local heat source	A3
5	Barakeh et al. (2017)	Development of a normalized multi-sensors system for low cost on-line atmospheric pollution detection	A4
6	Bibic et al. (2018)	New approach of measuring toxic gases concentrations: Application examples	A5
7	Jasinski et al. (2018)	Evaluation of the Commercial Electrochemical Gas Sensors for the Monitoring of CO in Ambient Air	A6
8	Masic et al. (2019)	On the applicability of low-cost sensors for measurements of aerosol concentrations	A7
9	Ghamari et al. (2022)	Evaluation and calibration of low-cost off-the-shelf particulate matter sensors using machine learning techniques	A8
10	Purwanto et al. (2019)	Design of Air Quality Monitoring System Based on Web Using Wireless Sensor Network	A9
11	Dahari et al. (2017)	Design of a measurement device for air pollution concentrations using an open-source electronics software and hardware system	A10
12	Apostolopoulos et al. (2022)	An IoT Integrated Air Quality Monitoring Device Based on Microcomputer Technology and Leading Industry Low-Cost Sensor Solutions	A11
13	Malik (2023)	Impact of Technology-based Education on Student Learning Outcomes and Engagement	A12
14	Saktiono et al. (2024)	Development of Air Quality Monitoring Device (AQM Dev) for Air Quality Measurement	A13
15	Rafaj et al. (2018)	Outlook for clean air in the context of sustainable development goals	A14
16	Zhao et al. (2020)	Does reducing air pollution improve the progress of sustainable development in China?	A15
17	Symonds et al. (2019)	MicroEnv: A microsimulation model for quantifying the impacts of environmental policies on population health and health inequalities	A16
18	Rao et al. (2016)	A multi-model assessment of the co-benefits of climate mitigation for global air quality	A17
19	Wang et al. (2024)	The Synergy Between CO ₂ and Air Pollution Emissions in Chinese Cities by 2060: An Assessment Based on the Emissions Inventory and Dynamic Projection Model	A18
20	Matos et al. (2019)	Modeling the provision of air-quality regulation ecosystem service provided by urban green spaces using lichens as ecological indicators	A19

Content Analysis Result

After the sources were collected, the study proceeded to the Step 2 Identification of Meaning Units and Step 2 Condensation and Coding. Corresponding to the research focus on developing a Teaching Learning Sequence (TLS) of constructing air quality measurement

instruments, this process resulted in the determination of four main contents in line with the analysis outcomes presented in Table 2.

Table 2. Content Analysis Result

No.	Content	Analysis
1	Types of air pollutants	<p>From the literature sources, air pollutants that are usually monitored can be categorized into three groups, namely: particulate matter, gaseous pollutants, and heavy metals by (Baldelli, 2021; Bloss, 2019; Maring et al., 2023; Valíček et al., 2012).</p> <ol style="list-style-type: none"> 1. PM includes PM2.5 and PM10, which represent fine particles with diameters less than 2.5 and 10 micrometers in diameter, correspondingly. These particles are very important because of their feature to penetrate deep into the lungs and enter the bloodstream, causing respiratory and cardiovascular health problems. 2. Gaseous Pollutants Smog forming gases are a group of several harmful gases. Carbon Monoxide (CO) Colorless, odorless gas, generated by incomplete combustion of fossil fuel. It is monitored because it may affect oxygen delivery to the body's organs and tissues. Nitrogen Oxides (NO_x) A group of Nitrogen dioxide (NO₂) and nitric oxide (NO) mainly from vehicle exhaust and industrial processes. They are important due to their key role in the formation of smog and acid rain, apart from their adverse impacts on respiratory health. The major air pollutants monitored are Sulphur Dioxide (SO₂) produced by volcanic eruptions; burning of fossil fuels such as coal and oil contributes to respiratory problems and formation of acid rain. Moreover, it monitors Ozone (O₃)-a secondary pollutant resulting from the reaction of volatile organic compounds and NO_x in sunlight, which is highly harmful to respiratory health and results in smog. 3. The third important category includes heavy metals. Lead (Pb) is one of the most monitored metals because of its toxic effects on the nervous system, especially in children. Other metals like arsenic (As), cadmium (Cd), nickel (Ni), and chromium (Cr) are also monitored due to their carcinogenic properties and other health hazards.
2	Types of sensors for measuring air pollution	<p>Several types of sensors are usually used for air pollution monitoring:</p> <ol style="list-style-type: none"> 1. Semiconductor Gas Sensors: These sensors respond to a wide range of pollutants like NO, NO₂, and CO in ambient air. The basis for these sensors is the change in electrical conductivity upon exposure to different gases. Measurements at differential temperatures are taken to indicate the identity of a specific pollutant. Semiconductor gas sensors are often integrated into networks of low-cost portable sensors; hence, they can easily be used for on-site monitoring of pollution (Barakeh et al., 2017). 2. Electrochemical Sensors: These low-cost sensors measure concentrations of toxic gases, including CO and NO₂, in real-world scenarios like public garages and urban streets. They generate a current proportional to the concentration of the target gas, produced through a chemical reaction between the gas and an electrolyte inside the sensor. Electrochemical sensors are commonly used for continuous diurnal monitoring and mobile measurements (Bibic et al., 2018; Jasinski et al., 2018). 3. Particulate Matter (PM) Sensors: These sensors measure the concentration of particulate matter suspended in the air, such as PM2.5 and PM10. Using light scattering technology, they detect and quantify particles by measuring the light scattered as particles pass through a laser beam. PM sensors are widely used for high-resolution spatial and temporal monitoring in environments

3	Designing device to measure air quality	<p>like coal mines and urban areas due to their portability and affordability (Ghamari et al., 2022; Masic et al., 2019).</p> <p>Steps for Air Quality Monitoring Device Development:</p> <ol style="list-style-type: none"> 1. Objectives and Requirements; It has to be clearly indicated whether the pollutant monitoring in discussion will be PM2.5, PM10, CO, or NO₂, among other parameters related to temperature and humidity. Therefore, it is necessary that this device can meet some needs for indoor or outdoor requirements clearly pointed out (Dahari et al., 2017; Purwanto et al., 2019). 2. Sensor and Component Selection; Sensor selection should be based on pollutants: MQ135 for gases, such as CO and NO₂; PMS5003 for PM2.5 and PM10; and DHT11 for temperature and humidity. The processing units may be microcontrollers like Arduino Mega 2560 or ATmega328, while optional communication modules can be ESP8266 or LoRa for wireless transmission. The power feeding can be done through batteries or solar panels (Apostolopoulos et al., 2022; Dahari et al., 2017; Malik, 2023; Purwanto et al., 2019). 3. Assemble the Device; Connect all sensors to the microcontroller, ensuring that wiring is well and securely connected. Design a durable casing that protects components against physical damage and environmental exposure. This is according to Dahari et al. (2017) and Malik (2023). 4. Software Development; Write and upload code to the microcontroller using platforms like Arduino IDE. Include features for data collection and processing. If using a seven-segment display, program it for real-time visualization; for advanced setups, integrate wireless data transmission (Apostolopoulos et al., 2022; Saktiono et al., 2024). 5. Calibrate and Test; Calibration involves comparing the device's readings with trusted reference instruments to ensure accuracy. Testing in various environmental conditions validates reliability and addresses potential issues before deployment (Purwanto et al., 2019; Saktiono et al., 2024). 6. Data Analysis and Visualization; For a seven-segment display, the device provides direct, real-time data. If wireless connectivity is included, data can be sent to a laptop or smartphone and visualized through dashboards or charts for better accessibility and analysis (Malik, 2023; Saktiono et al., 2024).
4	Benefits of measuring air quality	<p>Measuring air quality offers some key benefits, especially in the areas of health, environmental sustainability, and urban development, which actually go hand in hand with the United Nations SDGs.</p> <ol style="list-style-type: none"> 1. Health and Well-being (SDG 3) Air quality monitoring supports the improvement of public health through the identification and mitigation of air pollution risks. For instance, limiting air pollution could help prevent up to two million premature deaths globally by 2040 (Rafaj et al., 2018). On the other hand, air quality monitoring makes it possible to take appropriate interventions which have the impacts of enhancing the overall public health with lessened respiratory and cardiovascular burdens as observed by (Symonds et al., 2019; Zhao et al., 2020). 2. Environmental Sustainability (SDG 13, SDG 15) Air quality monitoring helps in mitigating climate change, SDG 13, by the identification of sources of pollution and thus allowing interventions which reduce air pollutants and greenhouse gas emissions (Rao, 2016; Wang, 2024). Further, it helps in protecting biodiversity and terrestrial ecosystems, SDG 15, since improved air quality has a direct positive impact on ecosystems and helps in promoting healthier habitats (Zhao et al., 2020).

3. Quality of Life (SDG 11)

It also provides the basis for sustainable city development through air quality monitoring in urban areas. Data inform policies aimed at reducing pollution, enhancing livability, and fostering urban resilience (Symonds et al., 2019). Besides that, it enables the optimization of urban green spaces-areas that contribute to a considerable reduction of air pollution and help improve the general urban environment of cities (Matos et al., 2019).

Category Selection

While all PM, gaseous, and heavy metal-type pollutants are important, not all are equally suitable for an education project. Particulate matter sensors, as well as heavy metal monitoring, require advanced equipment with high costs and, therefore, are inappropriate for a student-designed project. In contrast, gaseous pollutants, including CO and NO₂ emissions, can be monitored using relatively inexpensive semiconductor gas sensors, thus being much more accessible and achievable in education. The major advantages of semiconductor gas sensors are low cost, simplicity, and compatibility with portable designs. These sensors are very adequate for the detection of common urban pollutants, considering the educational purpose of introducing students to real environmental problems. Their simplicity ensures that students can engage with the project without being overwhelmed by technical complexity, allowing them to focus on critical thinking and problem-solving skills.

In this project, real-time air quality data visualization will be done in order to enhance interdisciplinary value and provide students with holistic learning. Instead of using simple displays like seven-segment screens that need wired connections, the students will develop a solution for wireless data transmission and visualization. The design is to send data from this device, which has a communication module like ESP8266 or LoRa, and view them on a laptop or smartphone with a user-built application or webpage. The method will therefore expose students to important information and communication technology skills in coding, user interface, and data analysis. The project is hence technologically and pedagogically enriching.

Emphasizing gaseous pollutants also provides the possibility of inculcating interdisciplinary notions, in particular those of chemistry, while studying gas properties, chemical reactions, and sensor mechanisms. This project addresses the PjBL objectives with enhancement in technical, analytical, and collaborative skills in conjunction with ICT use for data visualization. Besides, the monitoring of gaseous pollutants is directly related to urban contexts where these kinds of pollutants are usually found, making the learning relevant and effective. This research further develops the TLS project for the determination of gaseous pollutants and embeds real-time data visualization. It therefore tries to respond to the challenges of cost and complexity while enhancing the interdisciplinarity with the addition of environmental science, chemistry, and ICT.

TLS Design

Following Putri et al. (2024), the TLS is structured into four quadrants, each addressing a specific aspect of air pollution education to provide students with a comprehensive and interdisciplinary learning experience. Each quadrant is designed to guide students progressively from understanding the problem of air pollution to applying their knowledge in practical and

socially relevant ways. The TLS framework is visually presented in Figure 1 for clarity and coherence. Quadrant A deals with the causes, sources, and impacts of air pollution. Among the driving questions are: “Is air pollution dangerous?” and “How to measure air pollution levels in our area?” They are introduced to the major sources of pollution, like transportation and industrial emissions, through videos, infographics, and case studies presented by their instructor, after which they discuss the effects, including health risks and environmental degradation. Other aspects in which students are involved include air quality indices, such as *pollutant standards index* (PSI), in order to establish proper links between global and local air pollution problems.

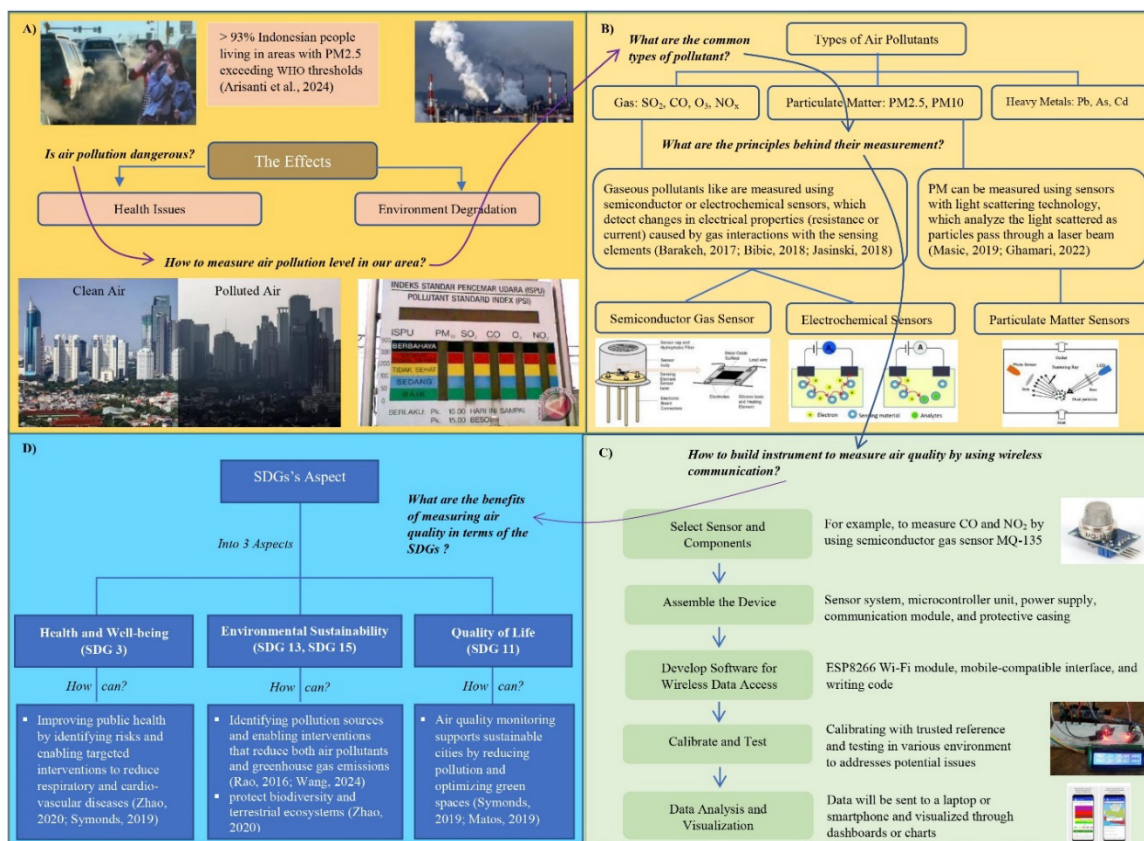


Figure 1. Design of the Teaching-Learning Sequence

Quadrant B addresses two basic questions: What are the main types of pollutants? What are the principles of their measurement? Bloss (2019) outlines critical measurement techniques, which align with the methodologies taught in this quadrant. The general classes of pollutants that students would study would include particulate matter (PM2.5, PM10), gaseous pollutants (CO, NO₂, SO₂, and O₃) and heavy metals (Pb, As, and Cd). They also learn about basic measurement technologies: semiconducting and electrochemical sensors detect gases in regard to changes in electrical properties due to their interaction with gas; particulate matter is studied as light-scattering technology where sensors analyze scattered light from particles passing through a laser beam. This quadrant deepens their understanding of how such technologies are applied to air quality monitoring and provides practical insight into real-world environmental challenges.

In Quadrant C, students explore the development of an air quality measuring device through wireless communication with the following question: How does one build a device for air quality measurement using wireless communication? First, sensors for the detection of gaseous pollutants such as CO and NO₂ have to be selected. Other main components besides the sensor (e.g., MQ135) are a microcontroller, such as Arduino, a communication module (e.g., ESP8266), and a power supply. Once the components are selected, students build the device by integrating the sensor system, microcontroller, power source, and protective casing. They move on to develop software through Arduino IDE, which permits data collection and wireless transmission; they usually create a mobile-friendly interface, like Blynk, for real-time monitoring (Chatzidiakou et al., 2023). The assembled device undergoes calibration and testing with trusted references and in varied environments to ensure accuracy and address potential issues. This is further sent to a smartphone for visualization. By this hands-on activity, students gain practical experience to solve real-world environmental problems. Real-world problem-solving activity is argued effective in preparing students for professional challenges (Abbonizio & Ho, 2020).

Quadrant D places center-stage the question “what are the benefits of measuring air quality in terms of supporting the SDGs?”. Students will discuss how their projects are aligned to SDG 3: Good Health and Well-being, SDG 13: Climate Action, SDG 15: Life on Land, and SDG 11: Sustainable Cities and Communities. For instance, regarding SDG 13, Arisanti et al. (2024) argue that the interconnectedness between air quality and climate change necessitates targeted environmental interventions, particularly those aimed at reducing vehicle emissions and preserving forest ecosystems. Similarly, Chatzidiakou et al. (2023) highlight how school-based air quality monitoring projects empower communities to take informed actions, making them valuable for promoting SDG 3 (Good Health and Well-being). Students further investigate how air quality monitoring informs health interventions, guides policies to reduce pollution, protects biodiversity, and promotes sustainable urban development by optimizing green spaces. It also looks at the role of mobile-based data in engaging the community for awareness.

The quadrant ends with the group presentations relating their projects to particular SDGs by showing the social, environmental, and educational benefits of air quality monitoring. Implementation of this TLS involves several disciplines. Physics covers concepts of electricity, electronics, semiconductors as sensor materials and working principles, and air pressure and temperature. Chemistry involves pollutant gases such as CO, NO₂, and O₃, the chemical reactions that take place in the atmosphere, and interaction of those gases in the human body, which cause health hazards. Biology involves the effect of pollutants on human health and ecosystems. Informatics is contributing in terms of coding and data processing for mobile devices. Indonesian language skills support oral and written communication in terms of preparing scientific reports. Geography relates the distribution of pollutants to topography, and Mathematics is used in sensor calibration and data analysis. Such interdisciplinary integration enhances collaboration among teachers and allows students to learn more meaningfully.

By integrating perspectives and methodologies from various fields, this interdisciplinary approach may foster the development of holistic and sustainable solutions (Yanniris, 2021). According to Abbonizio and Ho (2020), interdisciplinary education expands students' perspectives and gives them useful skills for overcoming sustainability obstacles.

Through project-based interdisciplinary learning, students are encouraged to think critically and collaboratively, enabling them to grasp the interconnectedness of environmental issues. By the same virtue, this approach equips learners with a wider and more integrated perspective, fosters interdisciplinary collaboration in teamwork, and hence enables them to develop comprehensive and effective solutions to real-world problems (MacLeod et al., 2023).

The TLS was evaluated by three experts in science education, who confirmed its validity qualitatively in several aspects, and the results are summarized in Table 3. All experts agreed that the TLS was feasible for classroom implementation. However, it had a number of suggestions from the experts, and the main point is on the school curriculum alignment where the TLS must ensure that students have appropriate competence to perform a project on making an air quality measuring device. It not only involves constructing the hardware part of the device but also making its software. Students are introduced to subjects of informatics at school, but the programming of a microcontroller and developing a display/ application might be challenging for students. In such a situation, detailed student guides and prepared support resources will be indispensable to assure that the learning process will be smooth and on time (De Vera et al., 2022).

Table 3. Summary of the Experts’ Evaluation on the TLS

No.	Evaluation Aspect	Results and suggestions
1	Relevance and suitability of the TLS content for senior high school students	The experts agreed that the TLS content was relevant to the senior high school science curriculum and appropriate for students’ cognitive level. The topic of air pollution was also considered contextual and closely related to students’ daily life.
2	Suitability of the TLS for interdisciplinary learning	The TLS was considered suitable for interdisciplinary learning because it integrates concepts from physics, chemistry, environmental science, technology, and informatics within a single project.
3	Clarity of the four-quadrant TLS structure	The overall structure was considered clear and systematic. However, the experts suggested strengthening the visual relationship between pollutants, sensors, and SDGs through additional diagrams, symbols, or colour coding.
4	Suitability of the learning methods used in the TLS	The use of PjBL, experiments, and technology integration was considered appropriate for achieving the intended learning goals. The experts also recommended adding reflective discussions and connecting activities with students’ local environmental context.
5	Usability and feasibility of implementation	The TLS was considered feasible for school implementation, particularly in schools with basic laboratory and computer facilities. The project was viewed as meaningful because it addresses real environmental issues.
6	Feasibility of tools and materials	The required tools and materials were considered relatively affordable and realistic, especially when implemented through group projects and supported by school facilities.
7	Suggestions for TLS improvement	The experts suggested improving visual explanations, strengthening the connection between pollutants and sensors, providing alternative activities for schools with limited facilities, and adding assessment rubrics and formative evaluation.
8	Potential challenges of implementing TLS	Potential challenges include limited facilities, insufficient teacher competence in technology and PjBL implementation, and limited instructional time. Teacher support and contextual adaptation were recommended to overcome these issues.

While integrating the different disciplines within the TLS, consideration on the subjects which are more or less capable of understanding each other is important. In view of this, the prerequisite knowledge for each subject needs to be ascertained and prepared well, as stated by Rico et al. (2021). Lastly, experts highly stressed careful consideration on materials and equipment that would be used in constructing the device. This not only includes associated costs but also the availability these materials so that students would face minimal difficulties in completing the project. This is essential for practical implementation and to ensure that projects are feasible within the educational context (Portillo-Blanco et al., 2024; Rico et al., 2021). Another consideration is the time needed to teach the project. Two of the experts suggest that a longer time is needed for teaching the topic to cover the complexities involved in integrating multiple disciplines effectively (Portillo-Blanco et al., 2024). By addressing these points, effectiveness and practicality can be further enhanced in the TLS.

The findings of this study, although not yet validated through classroom implementation, hold tremendous potential in addressing gaps in interdisciplinary PjBL and TLS for air pollution. Much of the existing literature has focused on the value of PjBL in developing problem-solving skills, increasing motivation, and allowing students to understand environmental challenges through interdisciplinary collaboration (MacLeod et al., 2023; Stokes & Harmer, 2018). However, most of these approaches have targeted pre-service teachers, leaving high school students underrepresented in air pollution learning (Mandrikas et al., 2017; Rico et al., 2021). The TLS developed in this study fills this gap by directly targeting high school students through hands-on projects, such as building air quality monitoring devices integrated with IoT-based wireless technologies.

This methodology nurtures student learning through experiential and contextually-based approaches while incorporating advanced tools to achieve interdisciplinary education and answering the call for innovative paradigms within the high school setting (Cleary et al., 2017; Maipas et al., 2021). The proposed TLS empowers students with vital skills relevant to the 21st century (problem-solving, critical thinking, and environmental consciousness) by linking theoretical content with practical applications, hence developing a strong foundation for future learning approaches.

Conclusion

Following the QCA approach, a TLS on air pollution has been developed and validated by experts. In this TLS, an interdisciplinary PjBL approach has been adopted where students are involved in making air quality measuring devices integrated with wireless data monitoring technology. TLS is composed of four quadrants that are: (A) Introducing the problem, understanding the problem of air pollution and the need for air quality measurement; (B) Understanding pollutants and measurement principles, understanding pollutants such as PM2.5 and CO, and measurement principles using technologies including semiconducting, electrochemical, and light-scattering sensors; (C) Project implementation, developing and testing air quality measuring devices integrated with up-to-date wireless technologies; and (D) Connecting to SDGs, discussing how the project meet SDGs including health improvement, climate action, and urban sustainability, and exploring their role in raising community awareness. This study contributes to interdisciplinary science education by developing a TLS

on air pollution for senior high school students through PjBL. The TLS integrates science concepts, technology, and SDGs within a real-world environmental project. It also introduces students to air quality monitoring and wireless data visualization. Practically, the TLS can support teachers of senior high schools in implementing contextual and interdisciplinary learning. The project activities may help students develop 21st century skills (such as problem-solving, critical and creative thinking), environmental awareness, and engagement with technology-based learning. While the developed TLS supplies a theoretical schema for an interdisciplinary education, it has to undergo empirical evaluation in classroom reality. Such testing, through worksheet designs for the students, is relevant not only to examine the efficacy and feasibility of TLS in relation to its nominated educational goals. Future research should focus on the actual implementation of TLS in a real classroom setting to observe its impact on the 21st-century skills of students, as well as students' environmental awareness. Moreover, the addition of a teacher training program in the implementation of TLS will help in scaling up because teachers will be better prepared to implement interdisciplinary and technology-driven learning experiences.

Credit Authorship Contribution Statement

Suana: Formal analysis, Writing – original draft, Writing – review & editing, Data curation. **Kaniawati:** Resources, Supervision, Validation. **Supriatna:** Conceptualization, Methodology, Supervision, Visualization.

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