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Inquiry-driven STEM Instruction: Enhancing Young Learners' Understanding of Air Pollution and Environmental Awareness

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Abstract

STEM education, which includes science, technology, engineering, and mathematics, has played an important role in preparing students for the future. When combined with inquiry-based learning, it provides a useful way to support students' curiosity, critical thinking, and problem-solving skills. This study examined how the use of inquiry-based learning in STEM education promote third-grade students improve their understanding of scientific concept of air pollution and their awareness of environmental issues. A mixed-methods approach was used with 45 students from a primary school in northeastern Thailand, who were divided into an experimental group and a control group. The experimental group took part in hands-on STEM activities about air pollution, while the control group learned through conventional teaching method. The results showed that the experimental group scored higher on understanding of air pollution. They also showed more awareness of environmental problems, including the ability to notice issues, and show positive attitudes toward solving them. These results point out that combining STEM education with inquiry-based learning could promote students learn science more deeply and care more about the environment. The findings provided useful ideas for teachers who intend to create meaningful and effective learning experiences.

Keywords: Scientific concepts, inquiry-based learning, STEM education, environmental awareness

■ Introduction

Environmental problems including climate change, air pollution, and the degradation of ecosystems have become major concerns worldwide (Wingard, 2001). Among these issues, air pollution was particularly severe, as it had become caused by human activities including factory emissions, deforestation,

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and the burning of fossil fuels (Vlek, 2007; Minelgaite & Liobikiene, 2019). These problems had strong effects on human health, wildlife, and the environment, making it important to educate young people about them. In response to these challenges, researchers and international organizations such as UNESCO (2024) and the OECD (2023) have called for the integration of environmental education into school curricula. These initiatives emphasize not only knowledge development but also the cultivation of students' responsibility and capacity to take informed environmental action. In this light, early education plays a vital role in building foundational attitudes toward sustainability.

Although many studies have shown the benefits of inquiry-based learning, there were still challenges in helping students connect scientific knowledge with real-world problems. Past research had often focused on teaching science content or improving test scores, but less attention had been given to developing students' environmental awareness at the same time. In addition, many science lessons remained too focused on memorization rather than helping students understand how science could solve everyday problems. As a result, students may struggle to see the importance of science in their lives or how they could take action to protect the environment. This gap in teaching suggested a need for new ways to design lessons that can both improve science learning and build students' environmental responsibility.

To address this gap, the present study designed and implemented a teaching approach called inquiry-driven STEM Instruction. This approach combined inquiry-based learning with STEM education, which includes science, technology, engineering, and mathematics. STEM education has been well known for improving problem-solving, creativity, and teamwork (Freeman, Marginson, and Tytler, 2019). It has also supported national development by encouraging innovation and social progress (Mohr-Schroeder et al., 2020). In this study, the inquiry-driven STEM Instruction focused on the topic of air pollution. The goal was to help students better understand scientific ideas while also becoming more aware of environmental problems. Moreover, inquiry-driven STEM instruction supported the principles of Education for Sustainable Development (ESD), which emphasized interdisciplinary thinking, learner-centered pedagogy, and real-world problem-solving. As young students developed their scientific understanding and moral awareness together, they are more likely to became active, responsible citizens in their communities and beyond.

To examine the results of this approach, this study aimed to answer two research questions. First, does inquiry-driven STEM Instruction improve students' understanding of scientific concepts related to air pollution? Second, does it increase their awareness of environmental issues? By answering these questions, this study expected to provide useful ideas for improving science teaching and building students' interest in solving real environmental problems.

■ Significance and Purposes

As global environmental challenges have increased, education systems have increasingly recognized the need to develop both scientific understanding and environmental awareness in young learners. This study addressed this need by exploring an instructional approach that integrated inquiry-based learning with STEM education to foster both conceptual knowledge and environmental responsibility. The combination of these two methods aimed to support students in constructing scientific knowledge through hands-on exploration while encouraging them to apply that knowledge to solve real environmental problems.

The significance of this study lay in its focus on primary school students, a group often overlooked in research that had emphasized secondary or higher education. By introducing inquiry-driven STEM Instruction at an early stage of schooling, this study demonstrated how young learners could begin to build scientific understanding and positive attitudes toward environmental issues, especially air pollution. The approach was expected to enhance students' engagement and provide them with opportunities to observe, question, and reflect on environmental problems within their communities.

Furthermore, the study offered practical value for science teachers and curriculum developers. It provided evidence on how structured, technology-supported inquiry within STEM activities could strengthen both conceptual learning and affective outcomes. In particular, the study responded to the need for instructional strategies that helped students connect classroom science with real-life experiences and environmental responsibilities. The findings may inform future efforts to develop science lessons that are more meaningful, active, and responsive to societal challenges.

This study also contributed to theory by linking inquiry-based pedagogy with affective dimensions of learning, such as attitudes and values toward environmental sustainability. While many previous studies had focused mainly on cognitive outcomes, this research emphasized the dual importance of content knowledge and emotional engagement. By applying a holistic view of science learning, the study aligned with socio-constructivist learning theories and current environmental education models that advocated for emotionally responsive and action-oriented teaching practices.

To guide the investigation, this study was designed to conduct following the research purposes:

1) Examining students' understanding of scientific concepts who learn with inquiry-driven STEM instruction about air pollution.
2) Examining students' environmental awareness who learn with inquiry-driven STEM instruction.

■ Literature Reviews

STEM Education through Environmental Literacy.

STEM education has been widely recognized as an effective approach to promoting essential 21st-century skills, including creativity, critical thinking, and collaboration. In recent years, researchers have increasingly emphasized the integration of environmental literacy within STEM education to encourage sustainability awareness and real-world problem-solving skills. This integration aimed to help students not only understand scientific content but also become more responsible citizens capable of addressing complex environmental issues. Several studies have supported this idea by highlighting how the inclusion of environmental topics in STEM curricula improved students' understanding of real-world issues and increased their motivation to develop solutions. For example, Kruawong (2018) found that embedding environmental literacy in upper secondary school curricula allowed students to apply STEM knowledge to local environmental challenges and develop a sense of responsibility. In particular, air pollution was often addressed as a critical topic due to its relevance to daily life and its serious impacts on health and the environment. Pertiwi et al. (2024) reported that STEM education based on project-based learning when focused on air pollution, helped students improve in four areas of environmental literacy: knowledge, cognitive skills, attitudes, and behavior. This supported the idea that teaching science in a context that students could relate to made learning more meaningful. Furthermore, the need to respond to global environmental challenges has led to greater awareness of the importance of environmental literacy as a tool to create stronger connections between students and nature.

In addition, researchers have emphasized the role of prospective teachers in promoting environmental literacy. Fakhriyah (2024) noted that future teachers could become role models who inspire their students to care for the environment. Training programs that included environmental learning through STEM approaches helped these teachers develop the skills and knowledge needed to promote environmental responsibility in the classroom. Moreover, Premthaisong and Chaipidech (2023) showed that combining STEM inquiry with environmental topics in primary education encouraged students to think critically about local pollution problems and identify possible solutions using scientific tools and reasoning.

Beyond improving knowledge and skills, environmental literacy also enhanced students' identity as change agents. When students saw their actions as meaningful contributions to environmental protection, their engagement with learning increased. According to Alkair et al. (2023), STEM programs that incorporated environmental sustainability themes through a problem-solving lens helped students develop both technical and ethical reasoning. These experiences built what some researchers referred to as a “green STEM identity,” where students began to see themselves as capable of making a difference.

Technology also played an important role in supporting STEM education focused on environmental issues. Innovative tools such as data sensors, simulations, and mobile apps enabled students to gather evidence, analyze patterns, and explore environmental systems in ways that were not possible through traditional teaching methods. Yun and Crippen (2023) noted that using digital technologies helped students make sense of abstract environmental concepts and connect them to daily life. These tools helped students link classroom learning to real-world challenges, deepening both cognitive and affective engagement.

Furthermore, Mohr-Schroeder et al. (2020) argued that environmental literacy must be framed within an equity-based perspective, especially in STEM education. Marginalized communities often faced the greatest environmental risks but had the fewest educational resources to address them. Integrating environmental themes into STEM instruction allowed educators to raise awareness of social and environmental justice issues, providing opportunities for all students to engage in meaningful inquiry and action. Overall, previous studies confirmed that integrating environmental literacy into STEM education could help students build a deeper understanding of sustainability challenges and equip them with the skills and mindset needed to address these issues.

An Inquiry Teaching Mode Based on STEM Education

Inquiry-based teaching has been widely accepted as a student-centered approach that encourages learners to ask questions, investigate problems, and draw conclusions based on evidence. When used in combination with STEM education, this approach supports the development of critical thinking, collaboration, and problem-solving skills. Numerous researchers have explored how inquiry-based teaching within STEM classrooms could improve students' learning experiences and prepare them to deal with real-world problems. For instance, Lian Zhai (2019) found that an inquiry-based STEM teaching model enhanced students' learning interest, knowledge application, professional and social skills, and promoted learning autonomy through collaborative problem-solving.

In elementary education, the integration of technology further supported the implementation of inquiry-based science education. Yun and Crippen (2023) examined how educational technologies were used in inquiry-based science classrooms and identified several key advantages. These included the ability to collect and analyze data, access digital learning materials, and connect classroom activities to real-life contexts. Moreover, Eshach and Fried (2005) argued that young learners were able to learn complex scientific ideas when instruction was age-appropriate and inquiry-based. Similarly, Patrick et al. (2009) found that inquiry-based science instruction in kindergarten improved students' conceptual understanding and motivated them to learn science. These findings provided a foundation for applying inquiry learning approaches to complex topics like environmental issues in primary education. In addition, inquiry-based STEM education also helped students make connections between scientific knowledge and environmental issues. Nicol (2021) described how inquiry-based science instruction encouraged students to engage with problems that mattered to their communities. By designing investigations and exploring solutions, students developed a deeper understanding of environmental concepts and became more motivated to act on environmental concerns. In addition, Demir and Kose (2022) explored the effects of STEM activities conducted in natural environments and found that such experiences improved students' environmental attitudes, increased their interest in STEM careers, and shaped their perceptions of engineering.

Moreover, combining inquiry-based learning with engineering design practices helped students understand the nature of scientific inquiry. Dedeturk, Saylan Kırmızıgül, and Kaya (2021) found that students who participated in STEM activities focused on designing and testing solutions showed stronger conceptual understanding of science topics. Similarly, Benek and Akcay (2022) reported that integrating STEM activities with socio-scientific issues helped seventh-grade students significantly improve their 21st-century skills. These included creativity, innovation, critical thinking, communication, and collaboration. The students also demonstrated gains in responsibility, problem-solving, and self-management. The study further showed that the development of these skills was sustained over time, indicating a long-term benefit of the instructional approach.

In summary, the integration of inquiry-based learning and STEM education offered a powerful teaching model that supported deeper learning, improved motivation, and promoted responsibility for solving real-life problems. This model appeared especially promising for addressing environmental challenges, where students were encouraged to think critically, explore solutions, and take positive actions in their communities.

Environmental Education and Student Engagement

Environmental education (EE) has been recognized as a key approach for fostering students' environmental awareness, knowledge, attitudes, and responsible behaviors. Ardoin et al. (2020) conducted a systematic review and found that EE programs with local relevance, community collaboration, and action-oriented activities promoted positive environmental outcomes. Such programs have helped students connect scientific understanding with conservation actions. Social factors have also influenced students' environmental concerns. For example, Stevenson et al. (2016) reported that adolescents' climate change concerns had been strongly shaped by personal beliefs, family influence, and peer discussions. Acceptance of human-caused climate change emerged as the strongest predictor of concern, while family discussions had contributed significantly to building environmental awareness.

While social influences and community-based programs play a key role in shaping students' environmental awareness and concerns, research also highlights the importance of curriculum design, instructional strategies, and student engagement in fostering pro-environmental attitudes and behaviors. For instance, Aminrad et al. (2013) investigated Malaysian secondary students and found that while knowledge about environmental issues showed a weak relationship with awareness, students with higher awareness displayed stronger pro-environmental attitudes. Their findings suggested that raising awareness might have a greater influence on attitude formation than knowledge alone. At the curriculum level, Imran et al. (2024) emphasized the urgent need to embed EE in educational policies. Their study showed that teaching strategies such as classroom discussions, field trips, and school-based environmental projects had effectively shaped students' sustainable values and attitudes. Student engagement has also played a vital role in enhancing learning outcomes in science education. Jimenez-Liso et al. (2021) introduced a model-based inquiry (MBI) approach to foster emotional, cognitive, and behavioral engagement. Their findings demonstrated that emotionally engaged students were more likely to sustain interest and actively participate in science-related environmental topics. Chowdhury (2016) highlighted the importance of integrating moral values and ethics into science education to encourage responsible citizenship. His study suggested that embedding ethical discussions within science lessons enhanced students' sense of social and environmental responsibility.

Additionally, Jackson et al. (2021) proposed an equity-focused STEM literacy framework promoting inclusive access to STEM and environmental education for all learners, particularly those from underrepresented groups. Overall, these studies confirmed that EE is most effective when it combines awareness building, emotional engagement, moral reasoning, social influence, and equity-focused educational practices.

Methods

This study employed a mixed-methods research approach using a non-equivalent control group pretest-posttest design. This design allowed for the comparison of student outcomes between an experimental group that received inquiry-driven STEM instruction and a control group that received traditional teaching. The mixed-methods approach combined quantitative data from tests with qualitative insights from student interviews, providing a more complete understanding of both scientific concept development and environmental awareness.

Participants

The participants consisted of 45 third-grade students (24 males and 21 females) from a university-affiliated demonstration school in northeastern Thailand. All students were between 8 and 9 years of age. The students were divided into two groups: an experimental group (n = 16) and a control group (n = 21). The experimental group received inquiry-driven STEM instruction focused on air pollution, while the control group learned through conventional science lessons followed the school's curriculum. Student group assignments were based on their existing class enrollment and were not randomized due to school administrative constraints.

The school selected for this study followed a national science curriculum and had integrated technology-supported instruction in several subjects. Teachers at the school had previously received training in active learning strategies, including the use of digital resources and cooperative learning structures. The science classes were held three times per week in well-equipped classrooms, and students had access to tablets and project materials. These conditions helped ensure the feasibility of implementing inquiry-driven STEM instruction effectively during the intervention.

Research Instruments

Two instruments were developed for this study. The first instrument was a conceptual understanding test, administered as both a pretest and posttest, to assess students' knowledge of air pollution. The test included ten multiple-choice questions (1 point each) and two open-ended questions (5 points each), totaling 20 points. The test content covered topics such as the definition of air pollution, causes and effects, and examples of pollutants. Three experienced science educators reviewed and validated the test items for content accuracy and age-appropriate language.

The second instrument was a semi-structured interview protocol used to assess students' environmental awareness after the intervention. The post-instruction interviews were adapted from Ozden (2008) and included open-ended questions related to students' understanding of environmental problems, personal responsibility, and attitudes toward environmental solutions. The interview protocol was piloted and refined before the full study.

Data collection and Data analysis

The data collection process in this study followed four main phases and involved both quantitative and qualitative methods. The participants were divided into two groups: the experimental group, which received inquiry-driven STEM instruction, and the control group, which received the school's science curriculum instruction as presented in Figure 1. The entire process was conducted over two weeks during the regular science class schedule.

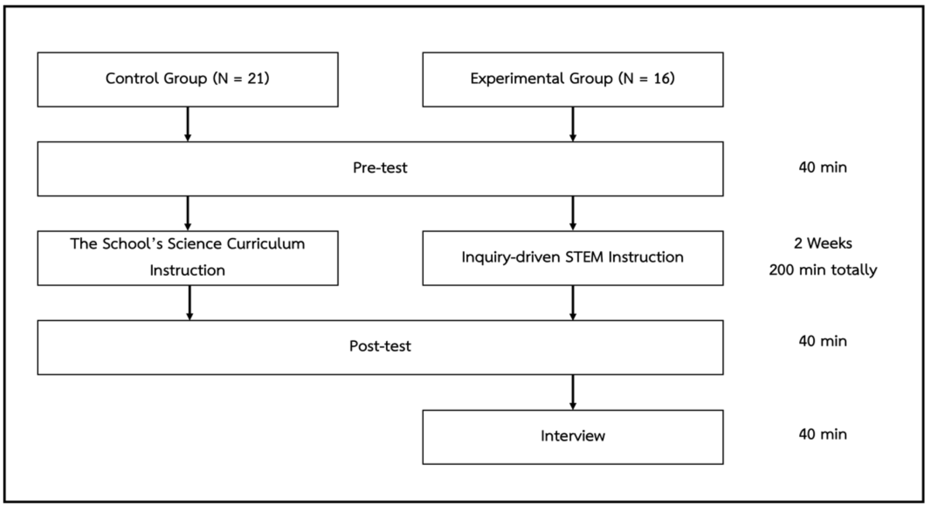

Figure *1*. The Data Collection Process

In the first phase, all participants completed a pretest designed to assess their baseline understanding of air pollution. The test included multiple-choice and open-ended questions and was administered in a 40-minute session under the supervision of the teacher-researcher. This step provided initial data to compare learning gains after the intervention.

In the second phase, both groups participated in a four-day instructional period with a total of 200 minutes of classroom time. The control group received instruction using the school's science curriculum teaching methods such as direct explanations and textbook-based activities. This curriculum incorporated active learning and inquiry-based strategies but followed a more structured and teacher-guided approach. The instructional process began with a warm-up activity where students reflected on the importance of air for life, engaging in short discussions to activate prior knowledge. During the brain activation phase, students analyzed and compared environmental conditions in two cities using the phenomena images to develop observation and reasoning skills about air quality. The investigation phase focused on classifying human activities contributing to air pollution by analyzing images provided in the textbook and participating in group discussions guided by the teacher. In the thinking process stage, students identified sources of air pollution through textbook-based exercises. To encourage further engagement, the teacher presented a video clip about volcanic eruptions, allowing students to distinguish between natural and human-made causes of air pollution. The lesson concluded with a presentation step, where students summarized their findings and shared their ideas with classmates. Unlike the experimental group, the control group did not use technology tools, conduct experiments, or participate in STEM-integrated during the instructional period. In contrast, the experimental group engaged in inquiry-driven STEM activities, including observing real-world pollution sources, conducting simple air quality experiments, and using digital tools such as videos and online simulations to explore the causes and effects of air pollution. Lessons also included group discussions and hands-on tasks that promoted problem-solving and active participation. The third phase involved a posttest using the same format and content as the pretest. It was administered to all students to measure changes in conceptual understanding after the learning period.

In the final phase, only the experimental group participated in semi-structured interviews. These interviews aimed to explore students' environmental awareness after completing the STEM activities. Each interview lasted approximately 40 minutes and followed a structured protocol adapted from Ozden (2008). Students' responses were recorded and transcribed for further analysis using qualitative content analysis. Moreover, figure 2 illustrated students completing their assignments with the aid of various technologies.

Figure *2*. Students Completing Their Assignments with The Aid of Various Technologies

For data analysis, Quantitative data from the pretest and posttest were analyzed using IBM SPSS Statistics. A Mann-Whitney U test was conducted to compare the conceptual understanding scores between the two groups. To quantify the difference between the two groups, the effect size was calculated following Rosenthal's (1994) method. According to Cohen's guideline, an effect size of 0.2 indicates a small effect, 0.5 indicates a medium effect, and 0.8 indicates a large effect. For the qualitative data, student responses from the post-instruction interviews were analyzed using content analysis. Responses were categorized based on four dimensions of environmental awareness: awareness of environmental issues, awareness of individual responsibility, general attitudes toward environmental problems, and general attitudes toward environmental solutions (Ozden, 2008). The analysis focused on identifying patterns in students' perceptions and the depth of their understanding regarding environmental challenges.

■ Results and Discussion

Conceptual Understanding of Air Pollution

The students' conceptual understanding of air pollution was evaluated through a pre-test and post-test administered to both the control and experimental groups. The Mann–Whitney U test was used to determine whether the differences in post-test scores between the groups were statistically significant. As shown in Table 1, the experimental group achieved a higher mean score (M = 17.31, SD = 2.96) compared to the control group (M = 15.56, SD = 3.33). The test results showed a statistically significant difference with a p-value of .025, indicating that students who participated in inquiry-driven STEM instruction demonstrated a greater improvement in conceptual understanding than those who learned through the conventional instruction. The effect size (r = .368) calculated using Rosenthal's formula suggested a medium effect according to Cohen's criteria, highlighting the practical significance of the instructional approach.

Table 1.

Statistical Result on Mann-Whitney U test for The Students' Conceptual Understanding of Air Pollution

Group	Students	Mean	S.D.	Mean Rank	Sum of Rank	Z	p-value	ES[a]
Control group	21	15.56	3.33	15.57	327	-2.237	.025*	0.368
Experimental group	16	17.31	2.96	23.50	376			

**p* < .05

[a] (Effect size = $Z/\sqrt{N}$, Rosenthal (1994)).

The results suggested that the instructional approach used with the experimental group was more effective in helping students understand scientific concepts related to air pollution. This improvement may be attributed to the nature of inquiry-driven STEM instruction, which encouraged students to observe, ask questions, investigate causes, and test ideas through activities that were closely related to real-life experiences. For example, students in the experimental group participated in lessons that included identifying local sources of air pollution, using digital tools to visualize pollution effects, and discussing practical solutions. These activities likely helped students construct a more meaningful understanding of the content compared to active learning with textbooks.

An interesting point that emerged from the analysis was the relatively high conceptual gains made by students in the experimental group despite their young age. Despite being only eight or nine years old, the students in the experimental group demonstrated the ability to understand abstract scientific concepts such as the causes and effects of air pollution. This result suggested that with appropriate support and engaging instructional strategies, young learners were able to develop meaningful scientific understanding. This finding aligned with previous research showing that young children were capable of engaging with complex science topics through inquiry-based learning. Moreover, Eshach and Fried (2005) and Patrick et al. (2009) highlighted that when early learners received developmentally appropriate and inquiry-focused instruction. They could effectively build both conceptual understanding and motivation for science learning. Another notable finding was the reduced variation in scores among students in the experimental group. The lower standard deviation (SD = 2.96) compared to the control group (SD = 3.33) indicated that the inquiry-driven STEM instruction may have supported more consistent learning gains across students with different academic abilities. This finding aligned with the equity-oriented conceptual framework for K–12 STEM literacy proposed by Jackson et al. (2021), which emphasized providing equitable access to meaningful STEM learning for all students, including those from underrepresented groups. This result is important for educators who aim to reduce achievement gaps in science classrooms. In addition, these findings were consistent with earlier studies. Dedeturk, Saylan Kırmızıgül, and Kaya (2021) found that students who participated in engineering design-based STEM activities showed an improved understanding of sound concepts. Similarly, Benek and Akcay (2022) found that socio-scientific STEM activities contributed to significant improvements in students' scientific thinking and collaboration skills, particularly in areas such as communication, creativity, and responsibility. The present study extended these findings by demonstrating that inquiry-driven STEM instruction could also be effective in supporting young learners' understanding of complex environmental science topics and promoting active engagement in real-world problems.

In conclusion, the results provided an evidence that inquiry-driven STEM instruction supported a deeper and more consistent conceptual understanding of air pollution among young learners. This finding highlights the potential of hands-on, student-centered teaching approaches to make science education more engaging and effective at the elementary level.

Environmental Awareness of Students

To examine students' environmental awareness after the instructional intervention, semi-structured interviews were conducted with the 16 students in the experimental group. Their responses were analyzed using four key dimensions based on Ozden (2008): Awareness of Environmental Issues (AEI), Awareness of Individual Responsibility (AIR), General Attitudes Toward Environmental Problems (GAEP), and General Attitudes Toward Environmental Solutions (GAES). The findings revealed that students developed a stronger awareness of environmental challenges, recognized their personal role in addressing those challenges, and demonstrated positive attitudes toward action and problem-solving.

1) Awareness of Environmental Problems (AEI)

In this dimension, students demonstrated an awareness that environmental problems such as air pollution have become more serious in recent years. They showed the ability to recognize the increasing severity and global impact of pollution. For example,

Student 01 remarked, "*Today's environmental problems are more serious than before. For example, air pollution affects us a lot because we need air to breathe*."

Student 05 added, "*Environmental awareness is moderate to high, depending on the type of problem. For example, with air pollution, I think awareness is high because I am concerned and view it as something close to me that can directly affect our lives.*"

These responses suggested that the students were not only aware of air pollution as a general issue but also understood its relevance to their daily lives and well-being. An interesting insight here was the students' ability to distinguish between different types of environmental problems and recognize the importance of proximity and personal relevance in shaping environmental concerns. This indicated the success of the learning experience in helping students connect scientific knowledge with real-world implications. These findings reflected previous research which suggested that environmental education programs have enhanced students' awareness by connecting environmental issues to their daily lives and personal well-being (Aminrad et al., 2013; Imran et al., 2024; Ardoin et al., 2020)

2) Awareness of Individual Responsibility (AIR)

Students also recognized the need for shared responsibility in addressing environmental issues. They expressed an understanding that while government and industry had roles to play, individuals must also act to create meaningful change. For instance,

Student 04 expressed, *"Everyone should share the responsibility for solving environmental problems because if only one group works on it, there will be little change. But if we work together, we can make a much bigger difference."*

Student 02 stated, "*As for me, I think the biggest pollution problems are burning and factories because I saw the news about people burning trash, plastic, and other things. It makes a lot of smoke and makes people get sick easily."*

These comments revealed that students had begun to take a more collective view of environmental responsibility. A particularly interesting point was that students linked their learning with external sources such as news media, demonstrating how classroom experiences could influence how they processed and interpreted environmental information in broader contexts. This development of individual responsibility was consistent with previous studies that highlighted how family influence and moral education could encourage students to view environmental protection as a shared societal duty (Stevenson et al., 2016; Chowdhury, 2016).

3) General Attitudes Towards Environmental Solutions (GAES)

In this aspect, students shared practical, everyday strategies for reducing air pollution and improving environmental conditions. Their suggestions reflected an ability to apply what they learned to realistic contexts. For example,

Student 07 said, *"We can start by doing simple things, like not burning trash and using a bicycle or walking instead of driving a car when going to places near my house."*

Student 08 added, *"People's lack of care for the environment may result in unclean air around the world. So, we should start taking action ourselves."*

These statements showed that students had internalized the concept that even small individual actions could contribute to broader environmental improvements. The emphasis on starting with simple, personal changes was especially noteworthy, as it reflects a sense of agency among young learners. Students' ability to propose realistic solutions echoes findings from Jimenez-Liso et al. (2021), who reported that inquiry-based science education fosters both emotional and behavioral engagement in environmental problem-solving. This finding suggested that inquiry-based STEM learning could help students not only understand problems but also feel empowered to take action.

4) General Attitudes Towards Environmental Problems (GAEP)

Finally, students expressed concern about harmful human behaviors that negatively affect the environment. Their comments reflected emotional engagement and a developing moral perspective regarding environmental protection. For example,

Student 11 stated, *"People shouldn't destroy nature, burn trash or forests because creating too much dust and particles is harmful to us. For example, various pollutants released into the air and breathed in can harm our health."*

Student 12 remarked, *"I feel that many people are destroying forests to build their houses, which destroys animals' habitats. Some people burn trash, which may be a cause of forest fires. It is harmful to us and other animals."*

These responses indicated that students were not only aware of the physical impacts of pollution but also expressed empathy toward other living beings affected by environmental damage. This moral concern towards the environment reflected prior research that emphasized the role of emotional engagement and ethical reasoning in building students' environmental attitudes (Ardoin et al., 2020; Chowdhury, 2016; Stevenson et al., 2016). It reflected a shift from learning facts to forming values, which was an essential component of environmental education. Overall, the students' awareness, sense of responsibility, and action-oriented attitudes observed in this study were consistent with prior research on environmental education. These findings supported previous evidence that well-designed learning experiences combining inquiry-based approaches, emotional engagement, and ethical reflection could effectively develop students' environmental literacy and encourage pro-environmental behaviors (Ardoin et al., 2020; Jimenez-Liso et al., 2021; Chowdhury, 2016).

While the interview findings demonstrated clear improvements in students' environmental awareness, it was important to note that these results reflected students' understanding, attitudes, and stated intentions rather than direct observations of behavior change. Students expressed concern about air pollution, recognized their individual responsibility, and described possible actions they could take. However, this study did not include behavioral assessments to measure whether students applied these actions in their daily lives outside the classroom. Therefore, the reported outcomes represented an increase in awareness and readiness to act, but further research was needed to examine long-term behavior change and the transfer of environmental responsibility into real-life practices.

To sum up, the interviews revealed that students who experienced inquiry-driven STEM Instruction developed a broad and meaningful understanding of environmental issues. They recognized both the urgency of the problems and their roles in addressing them. More importantly, they expressed a willingness to act and a growing sense of responsibility toward their communities and the natural world. These findings highlighted the value of integrating inquiry and STEM approaches not only for conceptual learning but also for fostering environmental citizenship in young learners. Overall, students' responses revealed that their understanding extended beyond factual knowledge toward ethical reasoning and community-based perspectives. Many students recognized the importance of shared responsibility, showed concern for animals and ecosystems, and proposed personal actions. These outcomes suggested that when environmental issues were explored through inquiry and STEM frameworks, even young learners could engage in systems thinking and show readiness for active citizenship. The findings also highlighted the role of student voices in environmental education, suggesting that their views should be considered when designing policies and programs that affect future sustainability.

■ Conclusion

This study examined the effects of inquiry-driven STEM Instruction on third-grade students' conceptual understanding of air pollution and their environmental awareness. The results showed that students who participated in this instructional approach achieved significantly higher scores in science concept tests compared to those who received traditional teaching. These students demonstrated a deeper understanding of air pollution, including its causes, effects, and possible solutions. The hands-on, inquiry-based activities allowed them to connect scientific content with real-life situations, which likely helped them build more meaningful knowledge.

In addition to improving science understanding, the inquiry-driven STEM Instruction also supported the development of environmental awareness. The students showed thoughtful reflections about environmental issues, such as the seriousness of air pollution, their personal responsibility, and the importance of finding and applying solutions. Their responses during interviews suggested that they had developed a stronger sense of care for their environment and a willingness to take action, even in small ways. These results indicated that the combination of inquiry-based learning and STEM education could be an effective way to encourage young learners to think critically and act responsibly.

An important finding of this study was the ability of young learners to understand complex environmental topics when they were taught through meaningful and active learning experiences. Although these students were only in third grade, they were able to discuss the impacts of pollution, propose practical solutions, and reflect on human responsibility. This showed that age should not be seen as a limitation when designing science lessons, especially when students are provided with the right support and engaging tasks.

In conclusion, this study provided evidence that inquiry-driven STEM Instruction was a valuable teaching method for helping students learn science and become more aware of environmental challenges. It also offered useful ideas for teachers and curriculum designers who aimed to promote deeper learning, environmental responsibility, and lifelong scientific thinking from an early age.

Limitations and Recommendations

Limitations

Although this study provided valuable insights into the benefits of Inquiry-Driven STEM Instruction, several limitations should be noted when interpreting the findings.

First, the sample size was relatively small, with only 45 students from a single university-affiliated primary school in northeastern Thailand. Because the participants were drawn from one school and were not randomly selected, the results may not have fully represented the experiences or outcomes of students in other educational settings or regions. Future research should involve a larger and more diverse group of participants across multiple schools to increase the generalizability of the findings.

Second, differences in students' backgrounds may have influenced their engagement and learning outcomes. While all students were in the same grade level, they may have varied in their prior knowledge of environmental issues, interest in science, or access to technology at home. In addition, factors such as classroom environment, teacher experience, and family support could have affected their performance. These variables were not fully controlled in this study. Future studies should aim to explore these factors in more detail and consider their influence on learning outcomes.

Third, the study focused only on short-term outcomes measured immediately after the instructional intervention. Although students showed improved conceptual understanding and environmental awareness at the end of the study, it remained unclear whether these outcomes would be sustained over time. Long-term retention of knowledge and behavioral change were important aspects of education. Therefore, future research should include follow-up assessments to evaluate whether the learning gains remain stable weeks or months after the instruction has ended.

Finally, the interviews were conducted only with students in the experimental group. While this helped explore the effects of inquiry-driven STEM Instruction, it did not allow for a direct comparison of attitudes between the two groups. Including post-intervention interviews with students from both groups in future studies could offer a more complete picture of how different teaching approaches influenced environmental thinking and awareness.

Recommendations

Based on the findings and limitations of this study, several recommendations are proposed for future research, classroom practice, and curriculum development. First, future research should involve larger and more diverse samples across various school contexts to improve the generalizability of the results. Including students from different regions and backgrounds would provide broader insights into the effectiveness of Inquiry-Driven STEM Instruction. Second, follow-up studies should examine the long-term impact of this instructional approach. Assessing knowledge retention and changes in environmental attitudes over time would help determine whether the observed benefits are sustained. Third, educators are encouraged to integrate inquiry-based STEM lessons into early science education. Engaging students with real-life environmental issues and hands-on investigations can promote both conceptual understanding and responsible attitudes. Fourth, professional development programs should support teachers in designing and implementing Inquiry-Driven STEM activities. Providing instructional resources and examples can help teachers apply these methods effectively.

Finally, future studies may explore the emotional and social aspects of students' environmental learning, such as empathy, responsibility, and care for nature, to strengthen the development of environmental citizenship. Researchers could also examine how digital literacy and access to technological tools influence the effectiveness of Inquiry-Driven STEM Instruction. Ensuring equitable access to digital learning resources is critical, especially when using technology to support environmental education in diverse classrooms.

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