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Interdisciplinary STEM program on authentic aerosol science research and students' systems thinking approach in problem-solving

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ABSTRACT

2 An increasingly important aim in education is to develop students capable of addressing complex, interdependent problems. This study integrates theories of situated learning, authentic science research, socioscientific issues, and interdisciplinary STEM education to construct a program for high school students. Drawn from Vygotsky and Dewey's philosophy of social constructivism, we developed a framework to incorporate situated learning, authentic science research, and socioscientific issues in fostering sustainable development competencies of systems thinking and problem-solving to provide opportunities for students to transition from newcomers to adaptive experts. Using qualitative methods,
1 we explored the development of a systems thinking approach in problem-solving related to climate change and air pollution in fifty-seven international school students in Taiwan. We found patterns of (1) systems thinking application in innovative solutions, (2) understanding the practices of authentic science research, and
2 (3) interconnections between science and society. The findings suggest the framework has relevance to high-value learning of systems thinking and for discussions of problem-solving in community contexts and future research directions.

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1. Introduction

The effects of climate change on the environment are being observed around the globe, which calls for an education that prepares students to address environmental problems that are complex and interdependent. Aerosols are fine suspensions of particulate matter of either biogenic or anthropogenic origin, but they can significantly impact our environment despite their small sizes. Furthermore, atmospheric concentrations of aerosols are interconnected to climatic variables through complex, nonlinear relationships (Stocker, 2014), which invariably considered a 'wicked problem' (Rittel & Webber, 1973). This problem is difficult or impossible to solve because of its challenging and interconnected nature. The complexity of the aerosols issue demands a multidisciplinary, systems thinking, and creative problem-solving approach. However, the World Economic Forum reported

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that the workforce seeks particular skill sets, including critical thinking and problem-solving; yet, these skill gaps continue to be high leading up to 2025 (Schwab & Zahid, 2020). Thus, there is an urgent need to equip the next generation of leaders with capabilities and insights to apply multiple knowledge systems to deal with ever-changing problem scenarios (Bybee, 2013). The key concern is for developmental relationships between multidisciplinary, systems thinking, and creative problem-solving of flexible cognitive mindset capable of handling novelty or change – an adaptive expertise mind. Hatano and Inagaki (1984) describe adaptive expertise as a combination of procedural and conceptual knowledge (or understanding), 'who not only perform[s] procedural skills efficiently but also understand[s] the meaning of the skills and nature of their object' (p. 28). In other words, rather than following routines, adaptive experts go beyond technical training and dynamically use accepted skills to investigate and expand present levels of competence. The merit of interdisciplinary sustainability education is highly considered given the complexity of sustainability issues and the need for holistic responses (Feng, 2012). For the past two decades, educators and education systems worldwide have been engaged in reassessing knowledge, skills, and mental models students need for success in today's rapidly changing and complex world (Soland et al., 2013). We need a paradigmatic shift in learning and teaching to cultivate students with competencies (Lave & Wenger, 2011; Sadler, 2009), particularly systems thinking and problem-solving, and encourage self-directed, exploratory, and interdisciplinary learning at all levels (Foster, 2002). 1 Systems thinking is a critical multidisciplinary skill that describes the cognitive flexibility needed to collaboratively address and work on complex social problems (Grohs et al., 2018).

Situated learning offers contexts for students to work on authentic activities, learn how to transfer knowledge to real-life situations, and engage in social interaction (Lave & Wenger, 2011; Sadler, 2009). Research on situated learning theory applied to various disciplines of science (Khishfe & Lederman, 2006; Walker & Zeidler, 2007; Zeidler & Nichols, 2009), mathematics (Frade & Da Rocha Falcão, 2008), geoscience (Donaldson et al., 2020) and artificial intelligence (Shih et al., 2021) were done. Findings have shown that situated learning is a robust and practical framework to highlight the tacit knowledge and skills, competencies-in-activities (Frade & Da Rocha Falcão, 2008), self-efficacy (Donaldson et al., 2020), promoting informed understandings of decision-making with the nature of science in mind (Walker & Zeidler, 2007), and interest and motivation combined with socioscientific issues (SSI) (Sadler, 2009). However, there is very little research on a systems thinking approach to problem-solving in situated learning activities.

Therefore, we designed an interdisciplinary STEM program in situation learning activities contingent with authentic aerosol science research, which aims to cultivate students' systems thinking and problem-solving competencies. Undoubtedly, our guiding research question is 'how does the interdisciplinary STEM program on authentic aerosol science research and a systems thinking approach shape students' problem-solving competency?'

2. Literature review

2.1. Authentic aerosol science research

Opportunities for students to connect with experts outside of school can positively 18 influence what is learned in school (Bransford et al., 2000). The *sociocultural theory*

proposes that such cooperative human activity is only possible because we all grow up and live within larger-scale social organisations or institutions (Bransford et al., 2000; Lemke, 2001). Thus, what is learned in school should be connected to out-of-school learning (Dewey, 2013). Experiences in authentic science research allow students to
23 engage in what scientists do in the real world of science. Such experiences should include student-directed tasks and more open-ended inquiries (Braund & Reiss, 2006) and discuss how scientists work, collaborate, and what role society plays in influencing science. In addition, the nature of science is a critical component of scientific literacy and the necessary knowledge for students to make informed decisions based on research findings (NSTA, 2020). This community of practice helps students engage with different *socioscientific issues* (SSI), improve their systems thinking and problem-solving, build content knowledge, and strengthen their augmentation practice (Sadler, 2011). SSI is an avenue to integrate controversial, socially relevant, real-world problems, such as climate change, genetic engineering, and abortion (Lee et al., 2020; Sadler et al., 2007;
8 Zeidler & Nichols, 2009). Zeidler (2015) has argued that SSI education ideally should: utilise personally relevant, controversial, and ill-structured problems that require scientific, evidence-based reasoning to inform decisions about such topics; employ the use of scientific concepts and social implications that require students to engage; integrate implicit and explicit ethical components with moral reasoning; and foster citizenship.

The study of aerosol is essential in understanding its overall effect on human health,
15 the environment, and climate change. Aerosol draws on many branches of science – the chemistry of air pollutants, the physics of the weather, the biology of emissions from trees, and the computer science needed to make models (Carslaw et al., 2021). Aerosols, either solid or liquid, have a signature size differentiating them from larger matters such as droplets. Aerosols have tremendous impacts on human life and the environment. For example, the current effect of aerosol on human life is the plausibility of transmission of the COVID-19 virus (Prather et al., 2020; Tang et al., 2020). Undoubtedly, understanding aerosols are essential to preparing mitigation strategies to address the negative impacts of aerosols on human life and the environment. Socioscientific issues are grounded in the interrelated paradigms of situated learning and communities of practice (Eastwood et al., 2012; Lave & Wenger, 2011; Sadler, 2009). To improve the overall quality of aerosol science education delivery, we would need to intentionally involve support for continued diversification of the science education entities in the system and encouragement of reciprocally collaborative, synergistic relationships (Falk et al., 2015).

2.2. Interdisciplinary STEM education

9 Science, technology, engineering, and mathematics (STEM) programs have become a priority in many countries' education policies. Although this acronym is omnipresent, and some know that STEM is related to science, technology, engineering, and mathemat-
16 ics, the meaning or significance of STEM is not clear and distinct. For some, STEM refers to education and careers in the hard sciences and mathematics, including computer science; for others, social sciences and other related fields are included (Marrero et al., 2014). We will follow Bybee's (2013) definition of STEM education as an interdisciplinary approach for students in learning and applying the concepts of STEM combined with real-world lessons in making connections between school, community, work, and the

global economy. We would also like to emphasise the importance of understanding how the world works through these four disciplines and applying this understanding in social and economic development and environmental conditions in all social spheres (Martín-Páez et al., 2019).

Zeidler (2016) argues that many STEM-based initiatives are missing the skills to envision the role of sociocultural-political contexts and understand the situational nature of these contexts to acquire prudence, morality, and character. Such connections with interdisciplinary STEM concepts and socioscientific issues will allow students to see the purpose of learning STEM content and inspire them as scientifically conscious and active citizens who will eventually participate in critical decision-making processes in society (Alcaraz-Dominguez & Barajas, 2021).

2.3. Systems thinking and problem-solving

Students must have expertise in scientific knowledge and practices related to the socio-scientific topic being researched to take educated action in science (Kolsto, 2001). Theories of expertise describe how novices incorporate new knowledge with prior knowledge to gradually become experts in their domain (Chi et al., 2014; Sawyer, 2011). We must consider helping students to be able to mix diverse specialities, adapt to changes, grow their knowledge, and become skilled in multiple disciplines or at the very least be able to apply systems thinking. With increasing complexity in today's wicked problems, students need to be trained to be cognitively flexible. This flexibility can distinguish further as the developing of adaptive expertise. Holyoak (2011) characterised adaptive experts as capable of drawing on their knowledge to invent new procedures for solving unique or novel problems, rather than simply applying already mastered procedures. This flexible, innovative use of information in unique settings is primarily attributable to adaptive specialists' higher capacity in systems thinking, which allows them to build and adjust their knowledge structures-based experiences from problem-solving situations (Bransford et al., 2000; Hatano & Inagaki, 1984).

Systems thinking is a critical skill in authentic science research and interdisciplinary STEM that helps learners think holistically about complex, real-world problems. Problem-solving is seen as a linear process and learning within a traditional class setting of solving problems with already given solutions. Complexity theory testifies to a more realistic strategy of problem-solving. Complexity theory provides how systems work and how they interact with each other. Those systems may be natural (climate) or primarily social (policy-making, different stakeholders' perspectives). However, like wicked problems, the relationships among variables are not linear, and small shifts can produce significant dynamic changes in systems (Peters, 2017). 'Problem-solvers' must grapple with complex interrelationships and emergent behaviour of systems. The National Research Council (2010, p. 3) defined systems thinking:

> The ability to understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system, adopting a 'big picture' perspective on work. It includes judgment and decision-making, system analysis, and systems evaluation, as well as abstract reasoning about how the different elements of a work process interact.

Systems thinking is an organisational methodology that creates a holistic approach to solving problems. Problem-solving needs to involve systems thinking to improve understanding and responsiveness of the problem because systems thinking examines the patterns and relationships of the parts of the system.

To better equip students as citizens and professionals, the curriculum would need to assist students in understanding and managing complexity and understanding diverse systems and phenomena in our world – it would be further meaningfully connected to the current problems and challenges. Students trained in higher-order thinking perform better in solving complex problems (Maani & Maharaj, 2002). The students' ability to transfer expert knowledge and invent new procedures for solving fresh issues, rather than simply applying already mastered procedures, is students' future learning moving towards developing adaptive expertise (Mylopoulos et al., 2018). Using non-routine or creative problem-solving skills, a skilled individual must examine a broad range of information, recognise patterns, and deduce the information to diagnose a problem. Ruiz-Primo (2009) states that problem-solving 'requires knowledge of how the information is linked conceptually and involves metacognition, the ability to reflect on whether a problem-solving strategy is working and switch to another strategy if the current strategy is not working' (p. 3). In addition, non-routine problem-solving includes creating new and innovative solutions, integrating seemingly unrelated information, and entertaining possibilities (Paewai et al., 2007). The authors argue that traditional, mechanistic thinking does not benefit students and the nature of complex, emergent interdisciplinary issues. Undoubtedly, research in this area is vitally needed, especially on how a systems thinking approach to problem-solving should be implemented and the possible impact on students.

Society's most urgent issues represent interconnections of *technical* (identifying and recognising scientific development, technology, and processes in the production of goods and services) and *contextual* (economic, political, ethical, and sociocultural) elements (Grohs et al., 2018). Therefore, a framework is essential to cultivate students' skills in systems thinking and complex collaborative problem-solving across disciplines in unpacking socioscientific issues. Grohs et al. (2018) designed a conceptual framework with three dimensions – problem, perspective, time – along with measure constructs associated with those dimensions. Consistent with this understanding of what is meant by a problem, Mayer and Wittrock (1996) define problem-solving as cognitive processing directed at transforming a given situation into a goal situation when no apparent method of solution is available. The *problem* dimension includes identification/structuring of a problem, information needs, underlying assumptions, goal clarity and constraints, and stakeholder identification and needs. The *perspective* dimension recognises that problem-solving involves the diverse stakeholders and the influence of their varied values, beliefs, and past experiences on the problem and the sustainability of any solution. Perspective and problem dimensions overlap because policy frames the problem-setting process for each stakeholder, and at times there will be conflicts with distinct framing of the problem itself. The *time* dimension is the reflective and predictive element of the problem-solving process of considering the past and future of given problems, stakeholders, and solutions (Grohs et al., 2018). All dimensions mentioned are intertwined and provide a framework for understanding a systems thinking approach to problem-solving that is thoughtful to the complex nature of wicked problems.

Grohs et al. (2018) incorporated the three dimensions with the technical and contextual elements in designing the seven constructs in their assessment tool: (1) problem identification: incorporates defining the problem, identifying and evaluating different resources, and finding assumptions and constraints within participant's reasoning, (2) information needs: participant's ability to connect additional information with their given problem statement to fully characterise the problem, (3) goals: identifying components that would be a successful plan, such as responses to short-term and long-term plans and the wickedness of their problem, (4) stakeholder/awareness: the ability to include relevant stakeholders, such as government, schools, scientists, engineers, corporations, local citizens, and so on in the participants' problem-solving and systems thinking process, (5) unintended consequence: ability to identify blind spots and generate solution(s) with these blind spots, either technical and/or contextual aspects, and can be short or long term in scope, (6) implementation challenges: focuses on expected barriers and considers necessary trade-offs with the participants' innovative plans, and (7) alignment: consistency with logical connections across elements of their plan.

2.4. Conceptual framework

Global issues are considered *wicked problems* deemed difficult or impossible to solve due to incomplete or contradictory knowledge, the number of people and opinions involved, attached economic burden, and the interconnected nature of these problems with other problems (Cook, 2015; Rittel & Webber, 1973). Due to the nature of wicked problems, knowledge of science, statistics, technology, engineering, politics, economics, and much more are necessary for coherent changes. Therefore, we proposed a framework that includes the interdisciplinary STEM and a systems thinking approach in problem-solving to address SSI, as SSI can be a platform to engage students by incorporating STEM-related content and complex and contentious social issues (Alcaraz-Dominguez & Barajas, 2021; Eastwood et al., 2012; Zeidler et al., 2019).

Situated learning theory can be a powerful intervention in combining interdisciplinary contexts, socioscientific issues, authentic science research, and a systems thinking approach in problem-solving. *Situated learning* in a *community of practice* offers students meaning from experts' engagement and adds to the community's beliefs, language, and culture. Collins (1988) defines situated learning as 'the notion of learning knowledge and skills in a context that reflects how knowledge will be useful in real life' (p. 3). When learners engage in authentic tasks in a social practise or process, they form a community of practice (Anderson et al., 1996), who share a concern, a set of problems, or a passion about a topic and who deepen their knowledge by interacting on an ongoing basis (Wenger et al., 2002). In a community of practice, learners move from *legitimate peripheral participation,* in which the learners or newcomers learn the underlying discourse, language, and norms to move toward *full participation* in the community of practice (Sadler, 2009; Wenger et al., 2002). Sharing knowledge requires interaction and informal learning processes such as storytelling, conversation, coaching, and apprenticeship (Sadler, 2009; Wenger et al., 2002).

In Figure 1, our conceptual framework shows *legitimate peripheral participation* as newcomers become adaptive experts using authentic science research, interdisciplinary

STEM-based approach, and a systems thinking approach in problem-solving. The themes of problem identification, information, goal, stakeholder awareness, unintended consequences, implementation challenges and alignment are inspired by previous research done by Grohs et al. (2018).

3. Methodology

The exploratory case study method was adopted for a contemporary phenomenon within 3 its real-world contexts (Yin, 2009) to explore how an interdisciplinary STEM program, aerosol authentic science research, and a systems thinking approach shape students' problem-solving.

3.1. Participants

A total of 78 ninth-grade students in Kaohsiung, Taiwan, participated in the Aerosol STEM Program. Fifty-seven students participated in the open-ended surveys, eleven students participated in the semi-interview, and seven groups' presentations were observed. All students were informed of the purpose of the study, given consent for collecting data, and ensured anonymity and privacy.

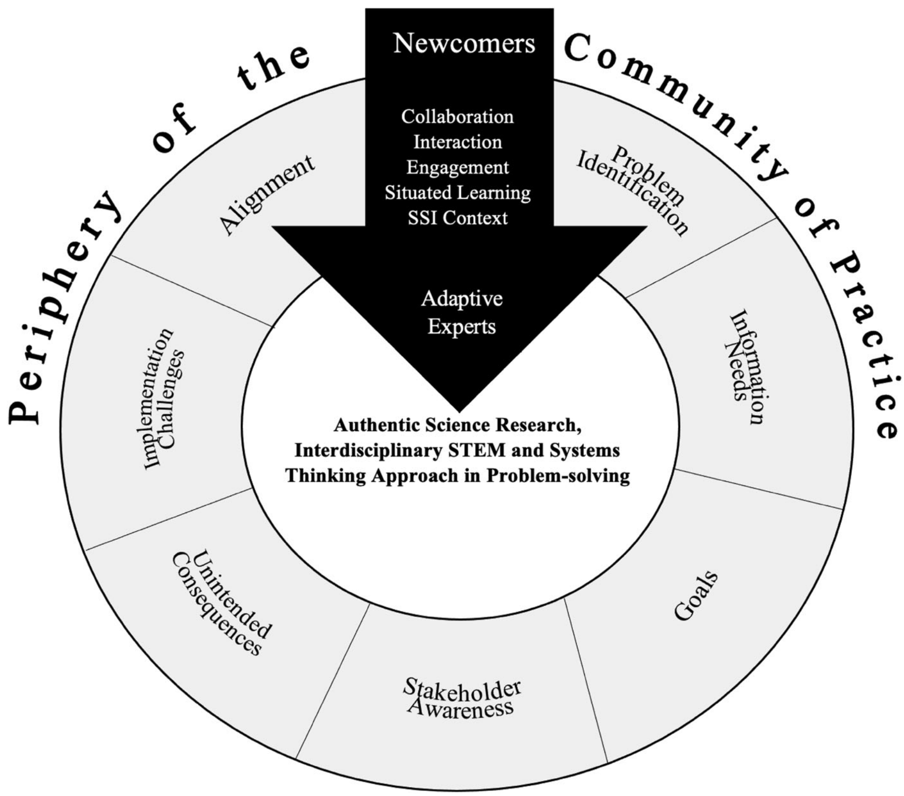

Figure 1. Communities of practice framework for authentic aerosol science research.

3 3.2. Interdisciplinary STEM program on authentic aerosol science research (short for 'Aerosol STEM Program')

A university-school partnership was formed to design the Aerosol STEM Program (Table 1) to support the ninth-grade ecology and climate change unit. Learning objectives ori- 20 ginated from Next Generation Science Standards (NGSS) using crosscutting concepts of cause and effect; systems and system models; and stability and change; also influence of science, engineering, and technology on society and the natural world (NGSS, 2022). The teacher and the university collaboratively decided on the topics and designed the Aerosol STEM Program to promote student participation in authentic aerosol research related to 24 the SSIs of air pollution and climate change through the lens of STEM disciplines and, 24 also, with social sciences, such as economics and political science. In week 1, students learned about the cycling of matter and aerosols involved in air pollution and climate change. In week 2, various global and local air pollution and climate change examples were introduced and discussed.

In weeks 3–5, the introduction of the UN Paris Accord Agreement gave insights into the legally binding international treaty and categorical solutions to help mitigate climate change. Students were instructed to choose a category and design a solution to solve 7 either a global or local issue of air pollution. Since one of the learning objectives of this unit was to develop students' understanding of the social aspects of science, such as various stakeholders' involvement and policy decision-making, the Iceberg Model (Maani, 2013) was used as a simple representation of a complex system to help students understand the multiple levels involved in solving a problem. The iceberg metaphor is used to show how dynamics influence issues or problems we cannot see, such as the structure that forms the framework within which we operate and the assumptions we hold about how things work. Students had to design their own Iceberg Model relative to their inquiry projects, carefully considering the relationships of four levels, including events, patterns/trends, underlying structures, and mental models. For the undergirding level of the mental model, the 'Tragedy of the Commons' (Hardins, 1968) was introduced with a hands-on activity and class discussions to highlight the concept of the 'common

Table 1. The aerosol STEM program.

Weeks 1–2	
Cycling of matter and flow of energy	Introduced the carbon cycle and graphing modelling of atmospheric carbon to demonstrate relationships of carbon emission and change in global temperature.
Solutions to global climate change	Introduced the UN Paris Accord Agreement categories of solutions: energy transition, industry transition, nature-based solutions, the scale of action, and climate financing.
Weeks 3–4	
Model of the greenhouse effect	Constructed simple models of the greenhouse effect and discussed how greenhouse gases retain heat.
Iceberg Model of systems thinking	Introduced the Iceberg Model of systems thinking tool to help students analyse the levels of an issue: events, patterns/trends, underlying structures, and mental models (Maani, 2013).
Weeks 5–6	
The Tragedy of the Commons	Demonstrate the Tragedy of the Commons and with examples of 'common good.'
Authentic Aerosol Science Research Field Trip	Students took a field trip to a nearby university for scientist presentations, an innovative board game, and lab visits on innovative technology to monitor and mitigate aerosols.
Weeks 7–8	
Interdisciplinary climate change project	Students presented their group projects by presenting their problem, innovative solutions, the Iceberg Model, and defending their ideas with a panel of teachers and university experts.

good' in a shared-resource system and the 'tragedy' of depleting or spoiling the shared resource.

In week 6, the students had a field trip to the university. First, three university professors presented their current aerosol science research studies: (1) aerosols, atmosphere, and climate changes, (2) fossil fuel PM_1 accumulation in marine biota, and (3) the chemistry of the hydrogen economy. After the presentations, the students played an innovative board game on air pollution to role-play different stakeholders in real-world scenarios. Then, students visited five labs in rotation:(1) an aerosol and biomedical science lab that investigates the physical and chemical properties of aerosols, (2) an aerosol LIDAR technology to monitor the optical properties of aerosols in the atmosphere, (3) an E-BAM $PM_{2.5}$ automatic monitor to track the emission of aerosols from merchant vessels in the nearly port, (4) spectroscopy and microscopy lab in identifying the properties of aerosols using infrared technology, and (5) an organic optoelectronic lab that creates innovative materials and technology in extracting hydrogen from organic materials.

In weeks 7–8, the culminating project was students' presentations of their innovative solutions to air pollution and climate change. Within these presentations, students introduced their ideas and incorporated systems thinking into their problem-solving.

3.3. Data collection

To understand students' hybrid competency, we collected three data sources, including open-ended questionnaire surveys, semi-structured interviews, and observations of student presentations. The fifty-six students completed the pre-and post-surveys with open-ended questions (see Appendix 1) relating their systems thinking and problem-solving perspectives. Semi-structured interviews (see Appendix 2) were administered to elicit students' hybrid competency shaped by the Aerosol STEM Program. Using the purposive sampling method, the participants of the interviews were chosen by the teacher because of their English language proficiency and candidness. Two interview sessions were conducted, six students in one group and five students in another group. All students from the interviews came from different project groups. Out of the eleven students, seven of the interviewed students were also observed when they presented their projects. Due to the scheduling conflicts, the presentations took place on multiple days, seven out of about eighteen group presentations were observed, video recorded, and transcribed for analysis. Observations were conducted to explore whether the Aerosol STEM Program and systems thinking shaped students' problem-solving competency.

3.4. Data analysis

The study triangulated three data sources, including open-ended questions, semi-structured focus group interviews, and observations of students' presentations using the themes developed by Grohs et al. (2018). Thematic analysis (Braun & Clarke, 2012) gives us snapshots of the Aerosol STEM Program and systems thinking influence on students' problem-solving by identifying and analysing patterns in the qualitative data. Once the data was coded from Grohs et al.'s (2018) themes, we then engaged in further rounds of coding using the *level of analysis* (Merriam & Grenier, 2019) to help us consolidate, reduce, and interpret interrelated elements of the Aerosol STEM Program and systems thinking to find patterns (e.g. 'the [Authentic Aerosol Science Research Field Trip] lectures really helped me understand and gained knowledge on my problem'). Using Hemmler et al. (2022) suggested qualitative coding and inter-rater reliability method, the authors used the themes from Grohs et al. (2018) as guidelines to brainstorm from the qualitative data (open-ended responses, interviews, and observations) in finding emerging codes. For example, we discovered 'problem', 'climate change', 'air pollution', and 'aerosols' as codes with 'problem identification'. When a complete consensus was made of the initial codes, the data was divided equally to the first and second authors. The two authors divided the dataset into two sets and each author coded individually in applying the codes to their half of the dataset. During the process, the coders met weekly to resolve any issues or questions about the coding and recalibrate the codes by combining redundant codes and disentangling divergent concepts within single codes, e.g. 'global warming' with 'climate change'. Code definitions were refined even more during this process, and coders developed intersubjective agreement on their application. Final codes, or sub-themes that emerged from the qualitative data from each of the themes: *problem identification* (e.g. climate change, air pollution, and aerosols), *information needed* (e.g. new information and ideas from experts, research to solve social issues, and different sources of information), *goals* (e.g. solutions and innovations, short-term and long-term solutions, working with stakeholders), *stakeholder awareness* (e.g. multiple perspectives and mental models), *unintended consequences* (e.g. may cause more issues), *implementation challenges* (e.g. economic and environmental obstacles and trade-offs; and mental models), and *alignment* (e.g. creative and critical thinking; and technical and contextual elements). At the end of this process, the authors switched datasets and applied the final codes. Subsequently, the individuals' datasets were compared to establish inter-rater reliability. Both authors found 90% consistency in the coding agreement. The ones that were not consistent weres discussed and reached a consensus.

Through the process of connecting the codes, we found patterns in the data across the three sets of data: open-ended survey, semi-structured interviews, and observations of the students' presentations. Similarities between separate groups of data were emerging at this stage, indicating areas of consensus in response to the research question, patterns and association of SSI, participation of a community of authentic science research, and a systems thinking approach in the students' problem-solving were revealed. To distinguish the source of the quotes with the associated patterns, we used 'S' or 'G' represents individual students or student groups; 'survey', 'observation', and 'interview' represent the data sources; 'problem' for problem identification, 'information' for information needs, 'goals', 'stakeholder' for stakeholder awareness, 'consequences' for unintended consequences, 'implementation' for implementation challenges, and 'alignment' represent the seven dimensions of a systems thinking approach to problem-solving (e.g. 'S1-survey-problem, information).

4. Findings and discussions

This study investigated how the interdisciplinary STEM program on authentic aerosol science research and a systems thinking approach affect students' problem-solving.

Three patterns emerged: (1) systems thinking application in innovative solutions; (2) understanding the practices of authentic science research; and (3) interconnections between science and society. The patterns are delineated in the following sections.

4.1. Systems thinking application in innovative solutions

The students demonstrated different perspectives (economic, political, social, technological, and scientific) in identifying problems and devising solutions to climate change or air pollution, e.g. 'considering multiple perspectives and choose the best solution' (S53-survey-problem, stakeholders) and 'view from different angles' (S56-survey-problem, stakeholders). Five of the seven groups presented their innovation of solutions to climate
24 change with short-term and long-term goals of involving stakeholders, such as businesses, government, and experts in the field of renewable energy, to implement and to have a successful outcome:

> Our goal is to decrease the [*sic*] emission released from fossil fuel burning power plants. To achieve this goal, we want to have 30% renewable energy consumption, possibly with … governments [enforcement]. [Business] firms are important on the innovations we are going to investigate to make renewable energy more popularised. We still need to balance the negative side of renewable energy, such as the price level for power plants. We also need reviews from solutions. An expert for feedback on our innovation to further improve. Hopefully, this goal will [take] two to three years depending on the investigation level and building the power plant. (G7-observation-goals, stakeholders)

Regarding the passage from the group's presentation on the theme 'Reducing Carbon Emission,' the reference to the short-term goal of decreasing emission from fossil fuels coupled with the long-term goal of the ongoing process of improvements to fulfil the 30% energy consumption using renewable energy sources within a time frame. The passage also illustrates the student's stakeholder awareness by mentioning the assistance of government agencies, business sectors, and technical experts for improvements and in reaching the project's goals.

Thirty-two of the 57 students in the survey, all groups in the observations, and eight of
12 the eleven students during the interviews spoke of the need for science, technology, and engineering applications and understanding the relationship between environment and social needs (health, energy, and economic growth). For example, one student said, 'we can put algae fuel our cars [to] generate energy, so we do not burn fossil fuels which creates pollution' (S10-interview, alignment), and another student stated, '[technical] innovations or regulations that we can implement in our society' (S29-survey-alignment).

Twenty of the fifty-seven students in the survey directed mentioned they learned from the experts during the Authentic Aerosol Science Research Field Trip, such as 'the lectures really helped me understand and gained knowledge on my problem' (S29-survey-information). All seven groups in the observations and nearly all the students in the interviews demonstrated informed science with the integration of contextual elements (social, economic, political, ethical, and moral); for example, in the presentation on the theme 'Addressing Water Scarcity with Seawater Desalination,' with this vignette:

> … even though the population growth rate is low, the total population was building increasing due to the fact that people live longer lives [than before]. Population growth also

contributes to industrialization, which increases the demand for water. As water demand increases, the overuse of our aquifers becomes a problem. (G2-observation-problem, information, stakeholders)

In the passage, the group researched the causes of the identified problems by their information needs, interconnecting relevant technical (development in science and technology and production of common goods) and contextual (socioeconomic, political, values) elements. With industries growing, these sectors need water for processing products. Consequently, water scarcity becomes a local problem. The group offered a desalination process using renewable energy to solve water scarcity. The group continued to discuss changing mental models of the stakeholders to be more vigilant in conserving water, such as policymakers needing to raise water taxes and society in general needs to learn how to save water usage and not take water for granted. Senge (1990) claims that systems thinkers are not only able to change their mental models but others to deal with the problem-solving process.

13 13 One of the operations for using system thinking in a problem-solving situation is expanding the systems' borders and exposing hidden dimensions of the system and interrelationships to other systems. Our findings on this issue are found in consonant with existing related scholarship. Twenty-seven students in the survey, early all of the students, and groups of the interviews and observations highlighted a new strength of seeing the 'big picture' and looking at national and global issues from a different perspective, e.g. 'considering multiple perspectives and choosing the best solution' (S53-survey-goals, stakeholders), which suggests a more informed holistic view of the problem. The findings of students' systems thinking by connecting the carbon cycle system to a network of interrelationships (technology, socioeconomic, environmental, political) help learners see the complete picture and contribute to problem-solving are supported by two earlier studies done. Assaraf and Orion (2005) utilised systems thinking strategies to assess, using a pre–post-test design, 13 junior high students' perception of the water cycle found meaningful improvements in the dynamic perception of the system and ability to find hidden parts of a system. Another study by Yoon (2008) in a ten-day genetic engineering curriculum and instructional unit employing a systems thinking approach with eleven grade 9 students showed evidence that complexity was harnessed on both behaviour and conceptual levels demonstrated by students' greater coherence and sophistication ideas as the unit progressed.

Understanding the issue's complexity in problem, perspective, and time dimensions is pivotal in problem identification and designing solutions. It is particularly interesting to observe that students have intuitions regarding ideas like creating alternatives and developing facsimiles of innovative technology. These findings imply, at the very least, that students can build more sophisticated understanding if learners are exposed more to a systems thinking approach. However, understanding and evaluating students' prior knowledge of the content (e.g. understanding of pollution and climate change, the ability to interpret statistics) needs to be considered more when doing this study.

4.2. Understanding the practices of authentic science research

Aerosol STEM Program offers opportunities to learn and understand scientific language in context by modelling real scientists. As adaptive expertise implies, new information can improve and refine previous ideas or open whole new avenues for achieving one's goal. As a result, part of the framework pertains to the inquiry and self-regulatory abilities required to recognise and analyse an SSI, determine what more knowledge is required, produce ideas, and utilise current knowledge to recognise pertinent information. The Aerosol STEM program provides the students with student-centred and inquiry-based interdisciplinary STEM education, which cultivate their critical thinking skills, such as communication, analytical, reasoning, synthesising, and thinking in various domains – the nature of science experience. Forty-two students in the survey, nine students in the interview and all groups in the observations mentioned the need to research and collaborate with others in solving climate change, especially with experts in the field of study with statements like 'work with partners' (S35 survey-stakeholders) and 'ask for help [from] more experienced people' (S56 survey-stakeholders).

Students' interdisciplinary climate change project was inquiry-based and purposely designed to explore climate change issues and generate a detailed solution. The Authentic Aerosol Science Research Field Trip allowed the students, and teachers, to see first-hand how scientists work, the nature of science, and how scientists use advanced technology to make analytical models. Thirty-seven students in the survey students stated in one form or another the *information needs* to solve air pollution, e.g. 'gained knowledge would ultimately help me to come up with mitigations to solve issues '(S29 survey-information, goals) and 'researching ways to solve the problems' (S4 survey-information, problem, goals). Students develop their ideas by interacting and asking questions with the experts during the Authentic Aerosol Science Research Field Trip. The Authentic Aerosol Science Research Field Trip's situated learning gave the students insights into how scientists work and their skills. Communities of practice allow the students to conduct legitimate peripheral participation, which indicates that integration into the culture of science is ideally situated in the context in which the practice of science occurs (Gardner et al., 2015; Sadler & McKinney, 2010). Students mentioned information they would not have learned in the school settings (e.g. 'taught us many professional information'). The findings are supported by previous related studies, showcasing that authentic science research programs can develop students' understanding of the science process and confidence in research. A study done by Ward (2016) of an environmental science outreach program for teachers compared to control and treatment groups found that the treatment group that conducted authentic research of their design had a deeper understanding of the process of science compared to their counterparts. Another study of situated summer research apprenticeships for high school girls found that the participants guided by scientists mentors felt more confident in their research as students assimilated into the community of practice (Conner et al., 2021). The students make informed decisions with information gathered from the scientists' presentations from the Authentic Aerosol Science Research Field Trip and their research based on the information gleaned from the field trip.

After the Aerosols STEM Program, students realised 'problem-solving uses logical thinking skills to solve a problem' (S25-survey-goals), and 'critical thinking and problem-solving could potentially help us find ways and solutions to climate change' (S2-survey-goals). The nature of science and critical thinking has been a goal for decades in science education. In our study, the students engage in argumentation to defend their innovative solutions to the audience, teacher, and scientist panel. In our observations, the modelling of high-quality critical thinking and argumentation skills during the Aerosol STEM Program played a role in developing these dimensions of higher-order thinking skills which is in concert with a study done by Maani and Maharaj (2002). This study analysed the complex problem-solving of ten business school graduate students, each with different systems thinking training levels, found that students with more systems thinking training and higher-order thinking perform better in solving complex problems. Another study with 30 middle school students measuring STEM perceptions and critical thinking found empirical evidence that STEM education developed critical thinking and perceptions of STEM in making real-life changes (Hacioglu & Gulhan, 2021).

The Aerosol STEM Program is an opportunity for students to engage, collaborate, and share ideas with scientists in a community of practice. To develop adaptive expertise, the students need to be in an environment that allows learners to use their knowledge in creative and innovative ways. Though this study demonstrates students' increased understanding of the nature of science, future studies should explore if the program increases comprehension and retention of the learning objectives over time.

4.3. Interconnections between science and society

The interconnections between science and society are learned and framed with shared experiences through a community of practice and interdisciplinary research, leading to creative ways to solve problems. Students referred to the moral and ethical consequences of the current patterns of climate change and the need for solutions. Twenty-eight students in the open-ended survey described stakeholder awareness, e.g. 'spreading awareness,' on the issues with others (politicians, energy companies, global and local citizens). Students had the commonality of the phrases such as 'mental model,' 'collaboration,' 'community,' and 'people.' One student stated how problem-solving is vital to individuals and organisations because it 'enables us to exert control over our environment' (S8-survey, goals).

During the semi-structured interviews, four students discussed information from the Aerosol STEM Program that they found interesting and relative to their identified problem. They were surprised at some of the information that they found in how much damage and lost lives relating to aerosol or air pollution:

> I have researched this, and around seven million people die from air pollution, according to the World Health Organisation. I think it is a huge problem because the particles of aerosol can cause both short-term and long-term effects. (S8-interview-problem, information needs)

The student's ability to connect additional information to the problem helps characterise the situation giving relevance to the student's task.

Unintended consequences and implementation challenges are common barriers and consider necessary trade-offs with the participants' innovative plans. Such as students dealt with their unintended consequences, implementation challenges, and alignment explicitly relating to their plans, such as 'financial costs' and 'changing people's mental model,' during the focus group interviews. One student stated that changing behaviours to have less or no greenhouse gases emissions would be counter-intuitive and, in a way, superficial in solving the issue:

> '… changing cars, changing your way of using stuff; and in the process of making [consumer goods], finding [solutions], but still making immense pollution [which] will not contribute directly to the solution. (S6-interview-consequences, implementation, alignment)

The student added that the most significant obstacle in making real and lasting changes are the government not willing to make these sustainable changes because of the high cost of overhauling infrastructures and replacing non-renewable energies with renewable energies. On the other hand, other students were more hopeful in the collaborative efforts of stakeholders, such as government, society, and innovators, in solving problems. For example, in the presentation on 'Alternative Energy Sources', the group offered a plan for stakeholders to work together to solve the issue of Taiwan's reliance on coal energy:

> Our goal is to decrease usage of coal energy and following government data on energy and [to] increase the use of our innovation which are renewable energies. For example, solar and wind energies. To be able to succeed, there are people responsible for this. The first one is government officials. They should promote and market clean energy. Then the energy companies can invest and focus on renewable energy sources. And lastly, the citizens [are] able to make proposals regarding clean energy … We need to track success by using official Energy reports by the government … For incentives, solar energy can have benefits such as government subsidies, and in longevity, it saves your money. Next, and if [society] changes their behaviours, such as [having] more care about climate change and personal carbon emissions. (G8-observation-goals, stakeholders, alignment)

The group in the vignette went further in discussing the technology that can be alternatives to coal energy and a need to balance economic growth and environmental health through the cooperation of the stakeholders and adopting new mental models. The group showed strength in the alignment in identifying components needed to bring a plan to be successful and able to see blind spots and generate solutions to the blind spots both with technological (scientific and technical development, and processes in productions of goods and services) and contextual elements (economic, political ethical, and sociocultural).

During the interview sessions, seven of the students discussed climate change's ethical and moral dilemmas, e.g. mental models allow 'citizens to use the water ethically … ' (G5-observation-stakeholders) and not reducing CO_2 emission for the next generation be 'unethical' (G3-observation-stakeholders). During one focus group interview, students mentioned that 'capitalism' was the cause of the environmental problems we face today:

> '… just going back to cost, I think it in order to solve this problem would probably have to change our systems in terms of like societal systems because currently, our role is kind of in the mess of capitalism. OK, I talked a lot about capitalism in that idea for probably 10 minutes. But basically, we have to create a new system that will assign values or resources because capitalism is incapable of accurately assessing resources because they value money more than anything'. (S4-interview-stakeholders)

This student further said that for any real change to happen, society needs to change government mentality to deal with sustainability issues because 'capitalism' and the government should fund researchers and transition from fossil fuels to renewable energy. In organisation systems, this dimension is expressed by social factors such as values, beliefs, and interests that lie under the surface. Also, to analyse the system's behaviour in the time dimension, one should present backward (retrospection) and forward (prediction) thinking skills (Grohs et al., 2018; Verhoeff et al., 2018). Maani and Maharaj (2002) refer to system thinking as a paradigm and argue that today systems thinking is needed more than ever as a society and the environment are overwhelmed with complexity.

Students in this study referred to their personal and local/global research issues and actively changed their lifestyles. They also commented on societies' moral and ethical obligations to mitigate sustainable matters, e.g. 'problem of extreme weather events and droughts became increasingly prevalent, the urgency of solving it also increased' (G2-observation-identification). Moral and ethical consideration is central to SSI negotiation (Zeidler & Nichols, 2009). Scientific literacy must entail negotiating and making decisions regarding complex social issues with theoretical and conceptual links to science (Fowler et al., 2009). The framework has the context that legitimises the learning from the students' perspective as intrinsically meaningful, e.g. 'I can start by raising awareness on the issue' (38-survey-stakeholders) and 'I looked at different technologies that are helping to solve climate change' (8-survey-implementation). Interdisciplinary STEM plays an essential role in the students' participation in practice and to work towards a solution to problems, skills, attitudes, and knowledge. In authentic science experiences, students have shown increased interest and motivation because they find the community of practice and SSI-infused curriculum more meaningful than formal settings (Bulte et al., 2006; Roth & Lee, 2004). In a study of mostly university graduates investigating unresolved, real-world agricultural and systems management, the systems thinking model found students' value in seeing the 'big picture' and the systems thinking program (Turner et al., 2022). Addressing the issue in social aspects and technical (knowledge and systems thinking) is pivotal in looking at the problems in multiple juxtapositions in order to make lasting solutions.

5. Conclusion

This paper has described a novel interdisciplinary framework grounded in communities of practice, SSI, Aerosol STEM Program, systems thinking, and problem-solving approaches. The results show that the framework provides practical designs and mindsets in preparing students for today's societies' complex, dynamic problems. Furthermore, the study indicates that the interdisciplinary STEM program can shape students' systems thinking and problem-solving competencies.

Based on our study, we highly suggest the need to incorporate three main elements at a minimum into curriculums relating to climate change and sustainability issues: (1) systems thinking application in innovative problem-solving; (2) understanding the practices of authentic science research; and (3) interconnections between science and society. Our study argues for the participation of the community in issues of climate change and sustainability issues. The university-school partnership intends to expose students to the various research, goals, and potential solutions of the scientists from the university. The authentic science research initiative gives students real-world experience in a systematic inquiry into problems relevant to their local communities. Courses should develop students' socio-environmental responsibility by providing tools for analysing and evaluating the social, economic, and environmental benefits, costs, and risks in making informed and responsible decisions even with imperfect information and complexity to engage in sustainable action (Talanquer et al., 2020).

Future studies might take up these questions, perhaps utilising the SEE-SEP model (Christenson et al., 2012) to assess higher-order thinking and interdisciplinary argumentation. Furthermore, a comparative approach can also help with the generalisability of the framework in different countries and grade levels.

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Appendices

Appendix 1. Open-ended survey questions

Pre-survey questions
(1) What does problem-solving mean to you?
(2) Do you feel you have gained problem-solving skills from the interdisciplinary unit? Please give reasons.
(3) How have you applied problem-solving skills in your life?
Post-survey questions
(4) What does problem-solving mean to you?
(5) Do you feel you have gained problem-solving skills from the Aerosol STEM Program? Please give reasons.
(6) How would you apply your problem-solving skills in the issue of climate change or air pollution?
(7) What is your research topic?
(8) How does your research topic relate s to aerosols, atmosphere, and climate change?
(9) What do you like about the Aerosol STEM Program and why?

Appendix 2. Semi-structured interview questions

List of possible interview questions for focus groups • For a future project, how would you relate the aerosol phenomenon/issue to this project?
• Do you think your project's solution can be applied to address the aerosol problem?
• Do you think your solution can have consequences?
• Do you think your solution has limitations or weaknesses?
• What challenges might you face when implementing your solution?
• What challenges might you face when implementing your solution?