Building a sustainable model of integrated stem education: investigating secondary school STEM classes after an integrated STEM project

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Abstract
This study investigated the sustainability of an integrated STEM education program. Two US high school science teachers and an engineering technology teacher sustained implementation of an integrated STEM curriculum after the conclusion of the funded program, TRAILS. Class observations were conducted to examine how the teachers implemented the integrated STEM curriculum and how they maintained integrated STEM teaching in a science and engineering technology education (ETE) teacher pair using science and engineering technology shared practices. After the integrated STEM lesson, their students’ academic achievements were compared to those of the students who previously participated in the project. The results reveal that the students showed no difference from the previous TRAILS students in terms of academic achievements as measured by STEM knowledge test scores, which may indicate that the teachers successfully maintained consistency and effectiveness of the implementation. Additionally, a twenty-first century skills survey was newly conducted to examine students’ growth in confidence in twenty-first century skills after they were taught the integrated STEM lesson. The students showed increased confidence in critical thinking, which indicates that the students benefitted from the teachers’ instructions even after the conclusion of the funded program and the absence of support. Based on the findings from the teachers’ experiences of multiple years of integrated STEM teaching, the study discusses how to better support teachers for the successful implementation of an integrated STEM curriculum as a sustainable education program in secondary schools.

Keywords Integrated STEM · Sustainability · Shared practice · Community of practice

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Introduction

With growing attention toward integrated STEM education in K-12 in the United States, developing instructional strategies and curricular materials to build sustainable models of integrated STEM education has become critical. To help teachers develop instructional strategies to integrate STEM subjects, teacher training through professional development, where they can build STEM education curriculum and increase the perception and understanding of STEM education fields, is extremely important (Kelley et al., 2021; Guzey et al., 2014). As Nadelson and Seifert (2017) posited, professional knowledge and confidence are paramount for teachers in successfully implementing integrated STEM education in their classrooms (Nadelson & Seifert, 2017). Science and engineering technology education (ETE) teacher collaboration is also vital. According to the National Academy of Engineering (NAE) Grand Challenges (GC) Committee, engineers are required to partner with scientists and explore scientific inquiries to understand our environment and improve our world (NAE, 2016). US Educational standards also require science and engineering practices to be shared (ITEEA, 2020; NGSS Lead States, 2013) for successful STEM education implementation. Furthermore, creating a sustainable Community of Practice to support STEM teachers is critical (Kelley & Knowles, 2016; Kezar & Gehrke, 2017). In a Community of Practice, teachers can share their concerns and deepen their knowledge by exchanging expertise with other teachers and experts on an ongoing basis (Kelley et al., 2021; Wenger et al., 2002).

To teach STEM subjects effectively in secondary schools, researchers presented the following key approaches within a well-designed integrated STEM education program: (a) STEM content integration, (b) inquiry-based instruction, (c) project- and problem-based instruction, (d) real-world problem solving, (e) collaboration, (f) design-based instruction, and (g) digital technologies (Kelley & Knowles, 2016; Nadelson & Seifert, 2017; Nguyen et al., 2020). With the goal of building a sustainable and replicable model of an integrated STEM education program, the current study examined an integrated STEM education project, Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS) (TRAILS), which incorporated inquiry- and design-based learning using 3D printing technology. During the project, TRAILS researchers, local industry partners, and graduate students partnered with the teachers and created a Community of Practice by providing teachers with professional development and supporting them to construct STEM knowledge and skills in an authentic STEM context.

Regarding the benefits of integrated STEM education, literature indicated that integrated STEM instruction exposes learners to meaningful contexts where they can enhance twenty-first century skills and motivation to learn STEM subjects (Nadelson & Seifert, 2017; NRC, 2014). However, even though researchers and educational standards recommend an interdisciplinary approach to teaching STEM content (Kelley & Knowles, 2016; Brown et al., 1989; ITEEA, 2020; NGSS Lead States, 2013), implementation of integrated STEM education by teachers and the influence of integrated STEM education on students’ STEM content knowledge achievement and twenty-first century skills are under-researched (Barrett et al., 2014; English, 2016; Honey et al., 2014; Khalil & Osman, 2017; Kelley et al., 2021).

After the three-year-long TRAILS project (2016–2019 school years, Year 1–3) ended, some teachers taught integrated STEM lessons again (Year 4), and the researchers wondered how the teachers implement integrated STEM education after the project. Specifically, as the current study (Year 4) participating teachers also participated in the TRAILS
for all three years (Year 1–3), we wondered how their instruction based on their experience of multiple years of teaching integrated STEM lessons affected students’ academic achievements and twenty-first century skills. Therefore, the purpose of the article is to investigate STEM classes after the project ended (with both financial and professional development support) to see if the TRAILS program provided the teachers with a practical model of integrated STEM education that motivates them to continue teaching STEM subjects in an integrative way.

**Research questions**

1. How do teachers implement integrated STEM lessons after participating in an integrated STEM project? (RQ1)
2. To what extent are the students’ STEM knowledge achievements different from those of the students who participated in the TRAILS project with program support? (RQ2)
3. To what extent are there differences between the students’ STEM knowledge achievement over the four-year period of the project during which the current teachers were involved? (RQ3)
4. To what extent do the confidence of students in their 21st century skills increase or decrease after learning an integrated STEM lesson? (RQ4)

**Literature review**

**Integrated STEM context: shared practices**

Integrated STEM education provides a context for scaffolding multiple aspects of STEM knowledge, which can be applied to authentic, real-world problems (Kelley & Knowles, 2016; Kelley et al., 2020; Han et al., 2020; Nadelson & Seifert, 2017; Stohlmann et al., 2012). Particularly, instructional activities in the integrated STEM context facilitate students’ learning of science through engineering design. By using engineering design and technology, students can test their science knowledge and apply it to real-life situations (Kelley & Knowles, 2016; Brown et al., 1989; NGSS Lead States, 2013).

Integrated STEM education is “the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning” (Kelley & Knowles, 2016, p. 3). Researchers and the US educational standards, such as the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) and Standards for Technological and Engineering Literacy (STEL) (ITEEA, 2020), emphasize connections between and across STEM disciplines and argue for integrating crosscutting concepts of STEM subjects in school curricula (Kelley & Knowles, 2016; Bybee, 2010). Specifically, the Next Generation Science Standards (NGSS) stress the interdependence of STEM disciplines and require teachers to integrate science and engineering explicitly by merging practices of the two disciplines. The shared practices of science and engineering addressed by NGSS include: (1) asking questions and defining problems; (2) developing and using models; (3) planning and carrying out investigations; (4) analyzing and interpreting data; (5) using mathematics and computational thinking; (6) constructing explanations and designing solutions; (7) engaging in argument from evidence, and; (8) obtaining, evaluating, and
communicating information (NGSS Lead States, 2013, Appendix F). Standards for Technological and Engineering Literacy (STEL) also noted the interconnectivity of STEM subjects and stressed the infusion of technology and engineering practices into integrated STEM education. According to STEL, technology and engineering practices include systems thinking, creativity, making and doing, critical thinking, optimism, collaboration, and attention to ethics (ITEEA, 2020). The core ideas connecting STEM disciplines and shared practices are scientific inquiry and engineering design (Apedoe et al., 2008; Kelley & Knowles, 2016; Kelley et al., 2020; Han et al., 2020; National Research Council [NRC], 2011; NGSS Lead States, 2013). According to researchers and the US educational standards, engineering design is a subject integrator in integrated STEM education, and engineering and technology can be a vehicle for science learning by realizing scientific inquiry (Kelley & Knowles, 2016; ITEEA, 2020; NGSS Lead States, 2013).

In summary, integrated STEM education allows scientific inquiry to be realized by technology and engineering design using authentic design tasks, and mathematical thinking plays a significant role as a helper in this process (Kelley, 2010; Kelley et al., 2020; Han et al., 2020; Han & Kelley, 2022). However, although integrated STEM education is innovative and beneficial for student learning, teaching an integrated STEM curriculum is complex as it requires not only content integration but also “teaching and learning across all three domains of learning: cognitive, affective, and psychomotor” (ITEEA, 2020, p. 4) (see Fig. 1).

**Benefits of integrated STEM education**

The goals of integrated STEM education are to help students prepare for STEM careers, build STEM literacy, increase interest and engagement in STEM subjects, and develop twenty-first century competencies (Pearson, 2017).

![Fig. 1 Three Domains of Learning for Technology and Engineering (ITEEA, 2020, pp. 121–122)](image-url)
Integrated STEM education helps learners develop problem-solving abilities by connecting subjects and real-world problems. While engaging in inquiry-based real-world problems, students enhance design thinking, which is required for a competent STEM workforce in the future (Kelley & Knowles, 2016; Dare et al., 2018; Jonassen et al., 2006; Moore et al., 2014). By integrating engineering and technology into science learning, students can develop, test, and apply their scientific knowledge to everyday real-world situations (Kelley & Knowles, 2016; Brown et al., 1989). Kelley & Knowles (2016) posited that “science education can be enhanced by infusing an engineering design approach because it creates opportunities to apply science knowledge and inquiry as well as provides an authentic context for learning mathematical reasoning for informed decisions during the design process” (p. 5).

Additionally, within the integrated STEM context, students can develop twenty-first century skills such as creativity, critical thinking, communication, and collaboration by addressing complex problems in our world (Bellanca & Brandt, 2010; Dare et al., 2018). According to National Research Council (NRC) (2011), twenty-first century skills include the ability to: (1) solve complex problems, (2) think critically about tasks, (3) effectively communicate with people using a variety of techniques, (4) work collaboratively with others, and (5) acquire new skills and information on one’s own (p. 1).

Moreover, integrated STEM instruction influences students positively on affective outcomes as well as cognitive outcomes by increasing the motivation to learn (Nadelson & Seifert, 2017; NRC, 2014), interest in STEM careers (Shahali et al., 2016), and attitudes toward STEM disciplines (Kelley et al., 2021; Guzey et al., 2014). Standards for Technological and Engineering Literacy (STEL) also noted that integrating technology and engineering into science and mathematics education will enhance student learning not only in the cognitive domain but also in the affective domain and psychomotor domain (Anderson & Krathwohl, 2001; Bloom et al., 1964) by increasing technological competencies (ITEEA, 2020). STEL addressed these three domains of learning for technology and engineering and the applicable levels of each domain (see Fig. 1). The cognitive domain includes six categories of Bloom’s revised Taxonomy of Educational Objectives for the cognitive domain (Remember, Understand, Apply, Analyze, Evaluate, and Create) (Anderson & Krathwohl, 2001). The affective domain categories (Receiving, Responding, Valuing, Organization, Characterization by Valuing) are based on Krathwohl et al.’s (1964) classification of learning objectives in the affective domain (Receiving/Attending, Responding, Valuing, Organization, Internalization/Characterization). Finally, the psychomotor domain categories presented in STEM include Observing, Imitating, Practicing, and Adopting (Kurt, 2020; Shown & Reed, 2020), which emphasize physical, reflective, and interpretive movements (Hoque, 2016).

Although efforts to integrate STEM contents in authentic contexts are increasing dramatically, further work remains to connect these disciplines in a deliberate way and apply STEM knowledge to real-world problems, since making connections across STEM disciplines in an integrated context still often remains implicit (Kelley & Knowles, 2016; NAE & NRC, 2009).

**Challenges of integrated STEM implementation**

For successful integrated STEM education, it is necessary to address the challenges that teachers confront in implementing integrated STEM education and reduce the barriers to teaching integrated STEM lessons (Kelley et al., 2021; Dare et al., 2018; Ejiwale, 2013;
Some barriers to advancing integrated STEM education that researchers identified are the following: (a) poor preparation and shortage of qualified teachers, (b) lack of investment in teacher professional development (PD), (c) poor preparation and inspiration of students, (d) lack of connection with individual learners in a variety of ways, (e) insufficient support from the school system, (f) insufficient research collaboration across STEM education fields, (g) poor content preparation, (h) poor content delivery and methods of assessment, (i) insufficient laboratory facilities and instructional media, and (j) lack of hands-on training for students (Ejiwale, 2013). Kelley & Knowles (2016) also identified some barriers that hinder integrated STEM education, which include rigid departmental agendas and requirements, inflexible content standards, and end-of-year exams.

To overcome the barriers to integrated STEM education, providing teachers with adequate support through the collaboration of school administrators, local communities, and educational policymakers is critical (Kelley & Knowles, 2016; Dare et al., 2018). Providing teachers with opportunities to participate in professional development where they can increase confidence and knowledge and learn how to integrate STEM content and STEM practices in instruction is also important (Kelley & Knowles, 2016; 2020a, b; Nadelson & Seifert, 2017; Shernoff et al., 2017). Moreover, increasing teacher self-efficacy through a Community of Practice is pivotal, as teachers’ comfort levels and their motivations to teach STEM content will also increase (Kelley et al., 2021; Nadelson et al., 2012). Likewise, studies show that teachers can increase their self-efficacy by participating in a Community of Practice as part of their professional development (Kelley et al., 2020; Han et al., 2020; Kelley et al., 2021; Ekici, 2018; McCollough et al., 2016).

TRAILS model for integrated STEM education

Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS) (National Science Foundation, award #DRL-1513248 aimed to build a sustainable and replicable model of integrated STEM education by) providing teachers with adequate support, including quality educational curriculum, professional development, and ongoing support from a Community of Practice. For this purpose, TRAILS had the initial goals: 1) Engage in-service science and engineering technology education teachers in professional development to build STEM knowledge and practices to enhance integrated STEM instruction; 2) Establish a sustainable Community of Practice of STEM teachers, researchers, industry partners, and college student “learning assistants”; 3) Engage grades 9–12 students in STEM learning through engineering design and 3D printing technology, and; 4) Generate strategies to overcome identified barriers for high school students in rural schools and underserved populations to pursue careers in STEM fields.

The TRAILS project integrates science, technology, engineering, and mathematics in an authentic way to enhance student learning and utilizes engineering design as the key to integrating STEM subjects.

The TRAILS project consisted of three cohorts: Year 1 was the 2016–2017 school year, Year 2 was the 2017–2018 school year, and Year 3 was the 2018–2019 school year, collaborating with a total of 30 teachers (15 science teachers, 15 ETE teachers) and 978 students (978 experimental group students) from 17 schools in suburban and rural school settings throughout the state of Indiana (experimental group with IRB consent forms submission).

The TRAILS research team developed an exemplar integrated STEM unit, Designing Bugs and Innovative Technology (D-BAIT): the unit consists of 10–12 sessions, including
biomimicry, life science, mathematics, engineering, and prototyping and 3D printing for practicing manufacturing (see Fig. 2 and Table 1). Students investigate water quality with the water insects they collected and research underwater creatures and their aquatic movements. They also learn about neutral buoyancy and biomimicry to apply these concepts in their prototype designs. Then students create fishing lure samples that mimic the functions of underwater insects and satisfy neutral buoyancy. For the entirety of the D-BAIT lesson, the biology teacher and the ETE teacher were encouraged to partner and teach both science and ETE classes collaboratively.

TRAILS summer professional development

Every summer, high school science and engineering and technology education (ETE) teachers participated in a two-week workshop with over 70 h of professional development (PD) and were trained to teach integrated STEM lessons for the following school year. Through professional development, TRAILS provided science and ETE teachers with practical and feasible approaches to support student learning in STEM subjects (Kelley et al., 2021; NRC, 2014; Ntemngwa & Oliver, 2018).

During the PD, the teachers engaged in an exemplar lesson, D-BAIT, developed by the TRAILS team to teach their students the following school year. Engineering design is the situated context in the TRAILS project and was used as a platform for integrated STEM education (Kelley & Knowles, 2016; Brown et al., 1989). In the D-BAIT lesson, teachers experienced scientific inquiry-based engineering design activities, which included engineering design brainstorming, aquatic specimen collection and identification, CAD instruction, 3D printing prototypes, and field-testing fishing lure prototypes. After participating in the D-BAIT lesson, science and ETE teachers were partnered, and each teacher pair created their own integrated STEM lesson with the help of the TRAILS research team. In the following academic school year, teachers delivered the D-BAIT lesson and the custom lesson they developed during the professional development in their classrooms.

Lesson implementation

Before this present study, the researchers conducted multiple case studies during the last year of the TRAILS project (Year 3) to capture how an integrated STEM lesson can be delivered to classrooms by science-ETE teacher pairs after they were trained at the PD. As the teachers were provided freedom in terms of how to implement the integrated STEM
| Learning activity              | Entomological science inquiry lab | Additive manufacturing (3D printing) of a fishing lure | Design analysis of lure prototype |
|-------------------------------|----------------------------------|-------------------------------------------------------|----------------------------------|
| Lesson description            | Aquatic entomology field lab to collect insects. Mathematical exercise to estimate insect diversity. Assess water quality using sampled insects | Parametric modeling software is used to create CAD designs for visualizing 3D models | Finite element analysis (FEA) features used within CAD parametric modeling software to generate simulations to test the strength of materials, calculate the volume of materials, and calculate buoyancy factors |
| Creativity                    | Students create individual inquiry questions regarding insects to investigate through observations | Students create unique design solutions applying characteristics of insects collected in the field to make an innovative fishing lure design | Students develop and implement prototype testing investigations to assess prototype performance and overall analysis of design |
| Critical thinking             | Students think about how insects become food for fish and how insects are indicators of water quality | Students are challenged to determine how to use innovative technologies to simulate insect motion, as observed in the inquiry investigation | Students generate testable hypotheses, investigate prototype solutions, and use features within innovative technology to generate evidence of proof of concept |
| Communication                 | Students record observations using field notes, videos, and digital photos to create a final lab report | Students generate multi-view CAD drawings providing key prototype specifications necessary to manufacture the prototype solution | Students document fair test investigations providing numerical data evidence to assess lure design performance |
| Collaboration                 | Through a Community of Practice, students report out individual findings to entire science and technology classes | Students share final design drawings across technology and science classes indicating how science inquiry observation data is used to create design solutions | Students will share design analysis investigation findings with all stakeholders within the Community of Practice |
lessons, they customized their own implementation plans, which they thought were optimal for their classrooms and school structure. From this previous case study that examined STEM teachers’ approaches to implementing integrated STEM lessons, the researchers identified the emergence of three distinct integrated STEM implementation models (Kelley et al., 2021, p. 43). (See Table 2).

The three models identified are important to understand how teachers implement integrated STEM lessons while overcoming barriers. Particularly, model 2 and model 3 indicate the collaboration of teachers from different domains within their school structure. Teachers in these models show their efforts to integrate STEM subjects within and across learning standards of two or more STEM subjects (Kelley et al., 2021).

Previously, Vasquez et al. (2013) presented four levels of integration of STEM disciplines: (1) Students learn concepts and skills separately in each discipline (Disciplinary); (2) Students learn concepts and skills separately in each discipline but within a common theme (Multidisciplinary); (3) Students learn concepts and skills from two or more disciplines that are tightly linked so as to deepen knowledge and skills (Interdisciplinary); (4) By undertaking real-world problems or projects, students apply knowledge and skills from two or more disciplines and help to shape the learning experience (Transdisciplinary) (p. 73).

However, Vasquez et al.’s (2013) models focused on levels of integration of STEM subjects (English, 2016), while the three models identified from the TRAILS focused on levels of teacher collaboration.

Even though each model has advantages and disadvantages, teachers found their own optimal ways to teach the integrated STEM lesson that fit their schedules, students, and school structure (Kelley et al., 2021).

The present study

The present study was conducted during the 2019–2020 school year (Year 4) to investigate how teachers implement integrated STEM education as a sustainable education program after participating in an integrated STEM education project. As the three models of implementation were captured during the TRAILS project, we wondered how the participating teachers implemented integrated STEM lessons after the project based on their previous experiences.

After the conclusion of the three-year-long TRAILS project, some teachers taught integrated STEM lessons again, including the D-BAIT lesson. Among them, three teachers (2 Science, 1 ETE) from two high schools, who participated in TRAILS for all three years (Year 1–3), volunteered to participate in this study. Institutional Review Board (IRB) consent forms were collected by the teachers using Purdue University protocol. Table 3 displays the demographics of the three participating teachers and their students.

Methods

For the first research question, “How do teachers implement integrated STEM lessons after participating in an integrated STEM project?” (RQ1), class observations were conducted to understand the nature of integrated STEM education through teachers’ experiences (Dare et al., 2018). The researchers visited one participant school two times as complete
| Model 1 | Model 2 | Model 3 |
|---------|---------|---------|
| **STEM content inclusion** | **STEM content integration** | **STEM content and practices integration** |
| Content is integrated in one classroom | Each domain teacher shared STEM content from domain | Content and practices are shared within a Community of Practice |
| One teacher adds one or more additional STEM domain content within the classroom | Each domain teacher teaches content, equipping students to become experienced with key practices and knowledge | STEM knowledge and practices inform the process taken by students |
| The approach is often called multidisciplinary | Two or more STEM domain’s information and practices are shared across classrooms | For example, science inquiry, engineering design, and computational thinking are informed by the integration process (crosscutting) |
| | Students become ‘experts’ sharing STEM knowledge | |
observers. Observations were recorded as field notes, which were “highly descriptive, including participants, setting, activities, behaviors of the participants” (Kelley et al., 2021, p. 36; Merriam, 1998). The field notes and observation records were cross-checked (member check) with the teachers of the class each time for validity (Gay et al., 2011). The class observed was an integrated STEM class that consisted of 16 science (biology) students and 15 engineering technology education students, and a science (biology) teacher and an ETE teacher taught this class collaboratively.

For the second research question, “To what extent are the students’ STEM knowledge achievements different from those of the students who participated in the TRAILS project with program support?” (RQ2), and the third research question, “To what extent are there differences between the students’ STEM knowledge achievement over the four-year period of the project during which the current teachers were involved?” (RQ3), we compared the students’ academic achievements of the participating teachers, who attempted to maintain effective integrated STEM instruction even without the funding after the project had ended, for those who participated in the TRAILS project in previous years. For the last research question, “To what extent do the confidence of students in their twenty-first century skills increase or decrease after learning an integrated STEM lesson?” (RQ4), twenty-first century skills pre- and post-surveys were implemented to investigate whether these teachers positively influenced students’ twenty-first century skills. (RQ4).

**Instruments**

**D-BAIT knowledge test**

The research team created the *D-BAIT* STEM knowledge test to evaluate student STEM content knowledge achievement from the integrated STEM lesson *D-BAIT*.

The initial *D-BAIT* STEM knowledge test was developed by a panel of six experts from entomology, technology, biology education, and engineering technology teacher education. Two high school biology and ETE teachers, who had more than 15 years of teaching, carefully reviewed the knowledge test for content and face validity. The instrument was then pilot tested with 429 high school students, and item analysis was conducted with the pilot test results. The final *D-BAIT* knowledge test consists of 20 multiple-choice items with three subject domains, including biology, engineering design, and physics. The overall Cronbach’s Alpha score obtained from the item analysis was over 0.7. The reliability score, which was calculated using the adjusted Spearman-Brown prophecy formula (Brown, 1910; Spearman, 1910), was 0.876.
21st Century Skills Survey

The 21st Century Skills Survey consists of 30 items within four subconstructs: critical thinking, collaboration, communication, and creativity (see Table 4). The five Likert-type score ranges from strongly disagree to strongly agree. Content validity was checked with a panel of experts from STEM fields (three STEM education faculty members, one two-year community college faculty, and two graduate students from STEM majors). Face validity was checked two times with three high school students. The survey instrument was pilot tested with 276 high school students, and an exploratory factor analysis was conducted. The Cronbach’s alpha reliabilities across the four subscales were: Collaboration = 0.826; Communication = 0.749; Creativity = 0.751; and Critical Thinking = 0.876 (Kelley et al., 2019).

Table 4 21st century skills survey

| Subconstruct      | Tasks                                                                 |
|-------------------|-----------------------------------------------------------------------|
| Critical thinking | revise drafts and justify revisions with evidence                     |
|                   | develop follow-up questions that focus on or broaden inquiry         |
|                   | create new, unique, surprising products                               |
|                   | identify in detail what needs to be known to answer a science inquiry question |
|                   | evaluate reasoning and evidence that support an argument              |
|                   | create ideas geared to the intended client or user                   |
|                   | develop follow-up questions to gain an understanding of the wants and needs of client or product users |
|                   | combine different elements into a complete product                   |
|                   | understand the questions that lead to critical thinking              |
|                   | justify choices of evaluation criteria                               |
|                   | gather relevant and sufficient information from different sources     |
| Collaboration     | be polite and kind to teammates                                      |
|                   | acknowledge and respect other perspectives                            |
|                   | follow the rules for team meetings                                   |
|                   | make sure all team members’ ideas are equally valued                 |
|                   | offer assistance to others in their work when needed                 |
|                   | improve my own work when given feedback                               |
|                   | use appropriate body language when presenting                        |
|                   | come physically and mentally prepared each day                        |
|                   | follow rules for team decision-making                                 |
| Communication     | use time, and run meetings, efficiently                              |
|                   | organize information well                                             |
|                   | track our team’s progress toward goals and deadlines                 |
|                   | complete tasks without having to be reminded                          |
|                   | present all information clearly, concisely, and logically             |
| Creativity        | understand how knowledge or insights might transfer to other situations or contexts |
|                   | find sources of information and inspiration when others do not        |
|                   | help the team solve problems and manage conflicts                     |
|                   | adapt a communication style appropriate for the purpose, task, or audience |
|                   | elaborate and improve on ideas                                        |
Data analysis

Academic performances (STEM knowledge test scores after the lesson) of the current year’s (Year 4) students were compared to those of previous years’ (Years 1–3) students that participated in the TRAILS project. Data from 42 classrooms (former participant classrooms = 39, current participant classrooms = 3) with 757 students (former participant students = 707, current participant students = 50) were collected from the 2016–2019 school years during the TRAILS project and the 2019–2020 school year of the current study. Considering the cluster effect of the data (intraclass correlation coefficient [ICC] = 0.319) as students were nested within each class, we used Multilevel Modeling (MLM) analysis using the HLM 8.0 Software instead of single-level analysis. For the nested data, single-level analysis can violate the independence of observations and reduce statistical power. On the other hand, MLM analysis can use clustered samples dependent on each other within the group they are nested in (Finch et al., 2019; Raudenbush & Bryk, 2002).

To compare Years 1–4 in terms of academic performance of the current study participating teachers’ students, Analysis of Variance (ANOVA) was used for the group analysis. Students’ growth in confidence in twenty-first century skills was also examined using the new instrument developed by the TRAILS team. The students who participated in the present study (Year 4) took the 21st Century Skills pre- and post-survey before and after they learned the integrated STEM lesson. To examine the influence of integrated STEM instruction on students’ (Year 4) confidence in twenty-first century skills, a matched pairs \( t \)-test was conducted using the SPSS software. A matched pairs \( t \)-test is frequently used to examine the change from pre- to post-survey to identify the effects of intervention (Duran et al., 2014; Xie & Reider, 2014).

Results

How do teachers implement integrated STEM lessons after participating in an integrated STEM project? (RQ1)

During the TRAILS project, the science (biology) teacher, Corey Adams, and the ETE teacher, Mark Zion, taught two integrated STEM lessons: one exemplar lesson, D-BAIT, and one custom lesson, Bumblebot, which they developed collaboratively during the PD. In the first and second years of participation in the TRAILS project, they taught the two classes separately (Model 2), but in the third year, they taught both science and ETE classes together for the D-BAIT lesson (Model 3). When they taught the integrated STEM lesson separately (Model 2), they switched the classes to teach their subjects to the students of other class subjects. In the fourth year, they taught together for the D-BAIT lesson again (Model 3) and separately for the custom lesson (Model 2). All the teaching materials were the same as the previous years.

The present study focused on the D-BAIT lesson. Corey Adams and Mark Zion taught the D-BAIT lesson together four times a week for the entire three weeks of instruction, and through the collaboration of the two teachers, science (biology) students and ETE students worked together throughout the D-BAIT unit and learned both disciplines in an integrative way.

During the first and second sessions of the D-BAIT lesson, students learned basic entomology and environmental science, such as aquatic habitats, food webs, adaptations,
evolution, ecosystem, food chain, and so on (Kelley et al., 2020, Han et al., 2020). On the first observation day, the third day of the D-BAIT lesson, students collected aquatic insects to investigate underwater creatures to research the natural environment and ecosystem. The next day, the teachers invited Purdue University entomology Ph.D. student for an entomology lesson. Students learned basic taxonomy and insect classification to understand the insect’s body shape and their adaptabilities. They also investigated the water insects they collected and applied the function of the underwater insect movements to create fishing lure sample prototypes. In this process, the teachers used the TRAILS resources, such as the insect identification index, TRAILS website, and entomology videos created by the TRAILS team. Later, the students used this knowledge to design fishing lure prototypes that mimic natural aquatic life.

To design a lure prototype, students used the CAD software program and a 3D printer, and most of the prototyping and printing parts were done by ETE students. Science (biology) students worked with ETE students to combine scientific inquiry with engineering design, and both biology and ETE teachers’ different expertise were integrated into their instruction.

Since the teachers taught the D-BAIT lesson together throughout the unit, they could collaborate and communicate during the classes as well as before and after. Even though they were teachers of different subjects, they were observed to emphasize the integration of other disciplines and constantly remind the students of what they would learn and why they were learning two domains of subjects together with another class of a different subject.

The students learned the lessons and completed the activities together throughout the unit, so they regularly met in a large media room, the largest room in the school. About 2–3 science (biology) students and 2–3 ETE students were grouped to work together for learning the subject knowledge, brainstorming, researching, designing the prototype, testing and evaluating, and redesigning.

To what extent are the students’ STEM knowledge achievements different from those of the students who participated in the TRAILS project with program support? (RQ2)

Multilevel Modeling (MLM) was conducted for this research question. All assumptions for MLM adequacy were checked, and the data were confirmed to be appropriate for the MLM analysis. The outcome variable, D-BAIT STEM knowledge test score (student STEM knowledge achievement), showed a normal distribution. Level-1 residuals and Level-2 residuals were independently and normally distributed with a common variance. For the MLM analysis, restricted maximum likelihood estimation (REML) was used, and the level-2 predictor was uncentered.

A total of 757 students (38.2% female students and 61.8% male students) were nested in 42 classrooms (23 science classes and 19 ETE classes) (See Table 5). The number of students nested in each class ranged from 5 to 64 (\(M = 18, SD = 11.579\)). The mean score of the D-BAIT STEM knowledge test was 10.55 (\(SD = 3.63\)). The D-BAIT STEM knowledge test score was set as the dependent variable, and the level-2 predictor (Year) was set as the independent variable. The categorical level-2 variable, Year, was dummy coded: 0 = previous years (Years 1–3), and 1 = current year (Year 4) (See Table 6).
Classroom variance in STEM knowledge achievement (unconditional model)

The summary of the Unconditional model is the following:

Level-1 model:

$$DBAITSCORE_{ij} = \beta_{0j} + r_{ij}$$

Level-2 model:

$$\beta_{0j} = \gamma_{00} + u_{0j}$$

Mixed model:

$$DBAITSCORE_{ij} = \gamma_{00} + u_{0j} + r_{ij}$$

where $DBAITSCORE_{ij} = D-BAIT$ score (STEM knowledge achievement) for student $i$ in class $j$, $\beta_{0j}$ group mean, $r_{ij}$ level 1 residual, $\gamma_{00}$ grand mean, and $u_{0j}$ level 2 residual (group effect).

From the unconditional model, intraclass correlation coefficient (ICC) was calculated to examine the classroom variance. The formula for the ICC is:

$$ICC = \frac{\tau_2}{\tau_2 + \sigma^2}$$

where $\tau^2$ between group variance, and $\sigma^2$ within group variance.

The ICC indicates that about 31.9% of the total variation in the STEM knowledge achievement ($D-BAIT$ score) is associated with the classroom difference ($\tau_0^2 = 4.3917$, $\chi^2 (41) = 349.9787$, $p < 0.001$).

Conditional model with classroom level predictor

The difference between the classrooms from the current year (Year 4) and those from the previous years (Years 1–3) in terms of student STEM knowledge achievement ($D-BAIT$ knowledge test score) was examined through a conditional model with the classroom-level predictor, Year (Years 1–3 = 0, Year 4 = 1).

The summary of the conditional model is the following:

Level-1 model:

$$DBAITSCORE_{ij} = \beta_{0j} + r_{ij}$$

Level-2 model:

$$\beta_{0j} = \gamma_{00} + \gamma_{01} \times (YEAR_{4j}) + u_{0j}$$

Mixed model:

$$DBAITSCORE_{ij} = \gamma_{00} + \gamma_{01} \times YEAR_{4j} + u_{0j} + r_{ij}$$

Table 7 displays the summary of the MLM results. The conditional mean (grand mean) of student STEM knowledge achievement ($D-BAIT$ test score) varies across classrooms ($\tau_0^2 = 4.0430$, $\chi^2 (40) = 318.9200$, $p < 0.001$) (Jeong & Choi, 2020; Suárez & Wright, 2019). However, the lesson implementation year was not found to be a significant predictor of student STEM knowledge achievement ($\gamma_{01} = 2.5222$, $t (40) = 1.959$, $p = 0.057$), which
Table 5  Demographics of the MLM data

| Science | ETE   | Male    | Female  | White   | Black  | Hispanic | Asian   | Other | Sum    |
|---------|-------|---------|---------|---------|--------|----------|---------|-------|--------|
|         |       | 479 (63.3%) | 278 (36.7%) | 468 (61.8%) | 645 (85.2%) | 27 (27%) | 57 (57%) | 19 (2.5%) | 9 (1.2%) | 757 (100%) |
indicates that the students of the current year (Year 4) did not show a difference in their academic performances compared to the students from the previous years (see Fig. 3).

Compared to the unconditional model ($\tau_0^2 = 4.3917$), 7.9% of variance is reduced by adding level 2 predictor, Year 4, to the conditional model ($\tau_0^2 = 4.0430$) (Raudenbush & Bryk, 2002).

**To what extent are there differences between the students’ STEM knowledge achievement over the four-year period of the project during which the current teachers were involved? (RQ3)**

To examine if the three teachers showed differences between during and after the TRAILS program in terms of their students’ STEM knowledge achievement (RQ3), an ANOVA test was conducted. Equality of variances of the dependent variable (D-BAIT score) across groups (Years 1–4) was assumed based on Levene’s test result ($p = 0.173$). Table 8 displays the descriptive statistics of the three teachers’ students. The results indicate that the three teachers’ students from Year 4 (After TRAILS) show better academic performances than those from Year 1 ($p < 0.001$), Year 2 ($p < 0.001$), and Year 3 ($p < 0.01$) (see Tables 9, 10).

| Table 6 | Variables and descriptive statistics |
|---------|-------------------------------------|
| Variables | Frequency (%) | M | SD | Min | Max | Skewness | Kurtosis |
| Student level | Level 1 | [NAME OF LESSON] score | 757 | 10.550 | 3.630 | 1 | 18 | 0.030 | 0.293 |
| Classroom level | Level 2 | Year (Current Year = 1, Previous Years = 0) | 42 |

| Table 7 | MLM models and results |
|---------|------------------------|
| Fixed effect | Unconditional model | Conditional model |
| | Estimate | SE | Estimate | SE |
| Intercept ($\beta_0$) | | | | |
| Intercept ($\tau_{00}$) | 10.5416*** | 0.3475 | 10.3562*** | 0.3483 |
| Year4 ($\tau_{01}$) | 2.5222 | 1.2878 | 2.5222 | 1.2878 |
| Variance Estimates Between-Classroom | Variance | Variance |
| Intercept ($\tau_0^2$) | 4.3917*** | 4.0430*** |
| Within-classroom ($\sigma^2$) | 9.3817 | 9.3842 |

*p < 0.05
**p < 0.01
***p < 0.001
To what extent do the confidence of students in their twenty-first century skills increase or decrease after learning an integrated STEM lesson? (RQ4)

To examine the current year’s students’ twenty-first century skills score increases from pre-to post-survey, a $t$-test was conducted (Year 4). Table 11 displays the descriptive statistics, and each pair shows pre/post-test scores of each category, critical thinking, collaboration, communication, and creativity. The ranges of Skewness and Kurtosis are between $-2$ and $+2$, which is the acceptable range to assume the normal distribution of the data (Gravetter et al., 2020; Sharma & Ojha, 2020). The result shows significant increases in the critical thinking category ($t(49) = 3.237, p = 0.002$). The other three categories (collaboration, communication, creativity) did not show a statistically significant difference between pre- and post-survey scores ($p > 0.05$) (see Table 12).

**Table 8**  D-BAIT score descriptive statistics of the focus group teachers’ students

| Year | N   | Mean | SD  | Skewness Statistic | Skewness SE | Kurtosis Statistic | Kurtosis SE |
|------|-----|------|-----|--------------------|-------------|--------------------|-------------|
| Year 1 | 52  | 10.40 | 3.637 | -0.118 | 0.330 | -1.009 | 0.650 |
| Year 2 | 50  | 9.92  | 3.238 | 0.259 | 0.337 | -0.590 | 0.662 |
| Year 3 | 98  | 11.17 | 3.343 | -0.480 | 0.244 | 0.024 | 0.483 |
| Year 4 | 50  | 12.88 | 3.088 | -0.836 | 0.337 | 0.683 | 0.662 |

Fig. 3  Distribution of D-BAIT STEM knowledge scores across classrooms by years. Years 1–3 previous years (during TRAILS). Year 4 current year (after TRAILS). Number of classes are in parentheses.
Summary of findings

The present study investigated the three teachers’ implementation of an integrated STEM curriculum after the TRAILS project, and we observed that the teachers’ experiences of participating in professional development and three years of integrated STEM implementation in a science-ETE teacher pair enabled them to continue teaching integrated STEM lesson effectively after the conclusion of the funded project (RQ1).

The students of the three teachers, who implemented integrated STEM instruction after three years of participation in the project, showed no difference from the previous TRAILS students in terms of STEM knowledge achievement (RQ2). Moreover, the students who the three teachers taught during Year 4 (after TRAILS) showed better academic performances than those who these teachers taught during Year 1 to Year 3 (during TRAILS) (RQ3). These results may indicate that teachers maintained and even improved their teaching in terms of student STEM knowledge achievement even after the project ended. Finally, students showed increases in their confidence in critical

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**Table 9** ANOVA test result

| Source        | Sum of squares | df  | Mean square | F      |
|---------------|----------------|-----|-------------|--------|
| Between groups| 253.766        | 3   | 84.589      | 7.596*** |
| Within groups | 2739.530       | 246 | 11.136      |         |
| Total         | 2993.296       | 249 |             |         |

***p < 0.001

**Table 10** Multiple comparison (post hoc test)

| I (Year) | J (Year) | Mean difference (I–J) | SE  | 95% Confidence interval | Lower bound | Upper bound |
|----------|----------|-----------------------|-----|-------------------------|-------------|-------------|
| Y1       | Y2       | 0.484                 | 0.661 | – 0.82  | 1.79 | |
| Y3       | Y4       | – 0.770               | 0.573 | – 1.90  | 0.36 | |
| Y4       | Y4       | – 2.476***            | 0.661 | – 3.78  | – 1.17 | |
| Y2       | Y1       | – 0.484               | 0.661 | – 1.79  | 0.82 | |
| Y3       | Y3       | – 1.253*              | 0.580 | – 2.40  | – 0.11 | |
| Y4       | Y4       | – 2.960***            | 0.667 | – 4.27  | – 1.65 | |
| Y3       | Y1       | 0.770                 | 0.573 | – 0.36  | 1.90 | |
| Y2       | Y2       | 1.253*                | 0.580 | 0.11    | 2.40 | |
| Y4       | Y4       | – 1.707**             | 0.580 | – 2.85  | – 0.56 | |
| Y4       | Y1       | 2.476***              | 0.661 | 1.17    | 3.78 | |
| Y2       | Y2       | 2.960***              | 0.667 | 1.65    | 4.27 | |
| Y3       | Y3       | 1.707***              | 0.580 | 0.56    | 2.85 | |

Fisher’s least significant difference (LSD) was used

Y1 Year 1, Y2 Year 2, Y3 Year 3, Y4 Year 4

*p < 0.05

**p < 0.01

***p < 0.001
thinking, which is one of the skills needed to prepare for the 21st-century workforce (RQ4).

However, as the Chi-Square result from the MLM analysis shows ($\tau_0^2 = 4.0430$, $\chi^2 (40) = 318.920$, $p < 0.001$), significant variation in student STEM knowledge achievement ($D$-BAIT knowledge test score) remains unexplained, which indicates that there exist additional classroom-level predictors that can explain the remaining variance in the intercept. Therefore, further analysis is needed to identify the classroom level predictors that influence student STEM knowledge achievement. For example, classroom teacher’s teaching skills, behaviors, and teaching experience, as well as socioeconomic status (SES) at the school level, may need to be further investigated (Armor et al., 2018; Huang & Moon, 2009; Nye et al., 2004; Perry & McConney, 2010).

### Table 11 Pre/post survey results descriptive statistics

| Pair | Mean | N | SD | SE | Skewness | Kurtosis |
|------|------|---|----|----|----------|----------|
| 1    | Post Crit | 44.660 | 50 | 5.017 | 0.709 | −0.140 | 0.245 |
|      | Pre Crit | 42.480 | 50 | 4.904 | 0.694 | −0.189 | −0.537 |
| 2    | Post Col | 39.000 | 50 | 3.922 | 0.555 | −0.628 | 0.281 |
|      | Pre Col | 38.440 | 50 | 4.146 | 0.586 | −0.206 | −0.814 |
| 3    | Post Com | 19.780 | 50 | 3.112 | 0.440 | −0.375 | −0.707 |
|      | Pre Com | 20.340 | 50 | 2.973 | 0.421 | −1.000 | 1.852 |
| 4    | Post Creat | 20.000 | 50 | 2.748 | 0.389 | −0.639 | 0.074 |
|      | Pre Creat | 20.180 | 50 | 2.723 | 0.385 | −0.412 | −0.364 |

*Crit* critical thinking, *Col* collaboration, *Com* communication, *Creat* creativity

### Table 12 Pre/post survey T-test results

| Pair   | Mean | SD  | SE  | t    | df | Sig. (2-tailed) |
|--------|------|-----|-----|------|----|-----------------|
| 2      | PostCrit – PreCrit | 2.18 | 4.762 | 0.674 | 3.237 | 49 | 0.002          |
| 3      | PostCol – PreCol | 0.56 | 3.980 | 0.563 | 0.995 | 49 | 0.325          |
| 4      | PostCom – PreCom | −0.56 | 3.252 | 0.460 | −1.218 | 49 | 0.229          |
| 5      | PostCre – PreCre | −0.18 | 2.336 | 0.330 | −0.545 | 49 | 0.588          |

*Crit* critical thinking, *Col* collaboration, *Com* communication, *Creat* creativity
Discussion

This study indicates the importance of providing teachers with ongoing help to implement integrated STEM education successfully. During the TRAILS project, teachers increased self-efficacy in teaching STEM lessons and the knowledge and ability to create integrated STEM lessons in professional development and Community of Practice (Kelley et al., 2020), which empowered the three participating teachers to maintain integrated STEM teaching.

Collaboration with a partner teacher and administrative support also seems to facilitate implementing new instructional strategies in teaching STEM curriculum (Kelley et al., 2021). Teachers collaborated as science-ETE teacher pairs to teach an integrated STEM curriculum and demonstrated different types of collaboration and subject integration (Kelley et al., 2021). For example, when the three focus teachers participated in the TRAILS project for three years, they taught both science and ETE class D-BAIT units collaboratively (Model 2) for the first and second years (Years 1 and 2), and in the third year (Year 3) they combined both classes and taught together throughout the unit (Model 3). In the current year (Year 4), after the conclusion of the project, the teachers taught the D-BAIT unit in this way again (Model 3), which they may have decided to be the best way for them to teach integrated STEM curriculum. However, this may not have been possible if the schools did not have the space, such as an LGI (Large Group Instruction) room, for the two classes to gather for doing the activities together. Also, if the school did not support teachers to teach collaboratively, collaborative teaching models (Model 2 and Model 3) may not be possible.

Moreover, building a sustainable Community of Practice is critical for integrated STEM education to be successful (Kelley & Knowles, 2016; Kezar & Gehrke, 2017). To build a Community of Practice for TRAILS STEM teachers, the TRAILS leadership team recruited over 20 STEM experts for teacher professional development in all three years of the project. These experts came from the workforce at the intersections across biomimicry, education, STEM research, and advanced manufacturing to present on the following topics: 3D scanning for design innovation, additive manufacturing, and applied research to advance STEM knowledge. These presentations provided knowledge with which TRAILS teachers could introduce authentic contexts to educate their students on current STEM practices and content; the practices were placed in the TRAILS learning activities and lessons planned by the teachers (TRAILS Annual Report, unpublished document). In Year 4, after the funded program had ended, the teachers we observed maintained their Community of Practice network and invited a TRAILS leadership team member, an entomology major graduate assistant, to their classroom as a guest speaker. They also participated in a state-wide STEM education conference and presented their experiences from the TRAILS project. The TRAILS leadership team tried to provide consistent support to teachers and arranged the follow-up sessions in Year 4. During a follow-up session-Indiana STEM education workshop-a total of 16 TRAILS teachers from Year 1–3 returned to campus, and 5 TRAILS teachers presented TRAILS lessons to a total of 80 in-service secondary STEM teachers from all over Indiana. In addition, after the conclusion of the TRAILS project, 10 TRAILS teachers reunited in the summer of 2019 to help format, refine, and build supplementary TRAILS curriculum and teacher resources. All these efforts reflect what Kezar and Gehrke (2017) emphasized for Sustaining Communities of Practice Focused on STEM Reform: (a) leadership development, distribution, and succession planning; (b) a viable
financial model; (c) a professionalized staff; (d) feedback and advice mechanisms; (e) research and assessment; and (f) an articulated community strategy (p. 323).

However, we admit that many teachers cannot implement integrated STEM education since they do not have partner teachers to collaborate with and flexibility in terms of availabilities and resources. Therefore, we recommend utilizing collaborative platforms that enable communications and collaboration between teachers as well as students, both in-school and out of school, and without the restriction of time and space (Lansmann et al., 2019; Leonardi et al., 2013). Also, teachers can share resources, including lesson plans, how-to videos, and professional CoP expert networks, within sustained websites. Specifically, by using online collaboration platforms, teachers may overcome restrictions on the time and place of different classrooms to communicate and collaborate. As integrated STEM education needs collaborative efforts of many people, not only teachers and students but also researchers, STEM experts, and integrated STEM CoP members, using online collaborative platforms will enable collaboration between them regardless of their availabilities.

In conclusion, for integrated STEM education to be implemented in secondary schools as a sustainable educational program, we need to listen to the beliefs, challenges, and understandings of teachers about integrated STEM education (Dare et al., 2018) and provide them with continued support. As the present study shows, the teachers, who were able to continue teaching integrated STEM lesson after the project, had three years of experience in the project, which may have reinforced their understanding and ability to implement integrated STEM education.

Limitations

The study has some limitations. First, as only three teachers and their students participated in the study, a relatively small number of the samples from these classes may not provide enough evidence to support the quantitative data analysis results. Second, the observation was only during one school year. To discuss sustainability, a longer period of investigation would be appropriate. Finally, class observations were conducted only two times. The observations were implemented in the 2019 fall semester, and further observations were not possible because of the COVID-19 pandemic starting in the following 2020 spring semester. As a result, the classroom implementation focused only on the D-BAIT lesson, and the custom integrated STEM lessons which the teachers developed during the TRAILS summer PD were not investigated. Consequently, the observations only described firsthand accounts of the research and further interpretations were not done, which may have caused credibility problems for qualitative data (Merriam, 1998). Therefore, the researchers recommend referring to the previous multiple case study, where the current participant teachers were also investigated (Kelley et al., 2021) as it provides more information that is based on additional class observations and teacher interviews during the final year (Year 3) of the TRAILS project.

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Declarations

Conflict of interest  The authors declare that they have no competing interests.

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