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A Systems Thinking Approach to Integrated STEM in School-Based Agricultural Education

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Abstract

The content and career cluster of agriculture, food, and natural resources (AFNR) provides opportunities for K-12 teachers to engage students to solve complex authentic problems that blend science, technology, engineering, and mathematics (STEM), yet limited research has been conducted on how to effectively leverage teaching and learning to integrate STEM using the context of AFNR through the school-based agricultural education program. This conceptual paper was developed through a collaborative sensemaking process focused on systems thinking as a way of knowing to integrate STEM within the contexts of AFNR, utilizing the SBAE program in the United States. A comprehensive career and technical education (CTE) program model of SBAE develops secondary education students' career readiness skills through classroom and laboratory instruction, leadership development, and supervised agricultural experiences. The literature was reviewed to describe the current status of integrated STEM in SBAE, including learning by doing, solving real-world problems, application of content knowledge in out-of-school and community-based settings, learner-centered pedagogies, and development of career readiness skills for the workforce. By employing systems thinking as the theoretical framework and integrated STEM as a conceptual framework, the authors engaged in collaborative sensemaking of their professional and scholarly experiences and proposed findings and discussion of a three-model framework (i.e., teacher, program, and learning approach) to support integrated STEM education through AFNR and SBAE. Limitations of the framework are also discussed. The AFNR career cluster was used as the context to discuss how the three-model framework (i.e., teacher, program, and learning approach) of integrated STEM through AFNR could be operationalized for SBAE. Discussion and implications of the three-model framework for other career clusters in career and technical education (CTE) and non-formal education in community settings are presented. Conclusions and recommendations are provided for advancing STEM integration in SBAE for teacher development, program development, and research.

Keywords: integrated STEM; systems thinking; teacher development; conceptual models

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1. Introduction

The agriculture, food, and natural resources (AFNR) sector plays a vital role in the global economy, encompassing industries for the production, processing, and distribution

of food, fiber, and natural resources (Alston & Pardey, 2014). Recent growth in the sector has been propelled by technological innovation, sustainability initiatives, and increasing global demand for food security and environmental stewardship (APLU, 2017; Gaffney et al., 2019). Advances in precision agriculture, biotechnology, and data analytics are reshaping traditional practices, enhancing both efficiency and environmental responsibility (Norris & Roberts-Hill, 2024; Rodrigues Barbosa et al., 2024). As stakeholders respond to these evolving demands, the integration of sustainability, innovation, and public engagement becomes increasingly critical (Dentoni et al., 2018; Jordan et al., 2014; McCune et al., 2021). Consequently, there is a growing need to prepare future agricultural professionals for these advanced practices (Albritton & Roberts, 2020; Wilson et al., 2025).

Career and technical education (CTE), also known as vocational education in the international context, provides skills-based learning for career development at both secondary and post-secondary levels (Advance CTE, 2023). Secondary CTE programs are organized into 14 career clusters, including AFNR, each outlining specific competencies required for success in related industries (Advance CTE, 2023). Post-secondary institutions such as community colleges and trade schools provide CTE programs that may lead to associate degrees, industry-recognized credentials, or certificates (Edgerton, 2022).

Although AFNR is often considered one of the oldest sciences, contemporary agricultural practices demand proficiency in STEM (Gao et al., 2020; Stubbs & Myers, 2016; Wilson et al., 2025). This underscores the importance of preparing AFNR educators to deliver rigorous, interdisciplinary STEM content (Miller, 2010). However, the persistent shortage of qualified STEM professionals also impacts SBAE (Schweingruber et al., 2014; Swafford, 2017). AFNR career pathways aim to prepare students with the skills necessary for sustainable and technologically advanced careers, thereby strengthening global systems (National Council for Agricultural Education, 2025). SBAE offers a systems thinking approach to integrated STEM through its three core components: classroom/laboratory instruction, FFA (formerly known as Future Farmers of America; currently known as the National FFA Organization), and supervised agricultural experiences (SAEs). These components collectively enhance STEM literacy (McKim et al., 2017; Scherer et al., 2019; Swafford, 2017; Stubbs & Myers, 2015). As illustrated in Figure 1, a comprehensive SBAE program can educate, engage, and transition students into careers or future education in STEM, business, and sustainability across the AFNR value chain (Park, 2024).

Classroom and laboratory instruction fosters agricultural literacy and contextualized STEM learning by integrating topics such as plant genetics, soil science, and animal anatomy (Eck et al., 2023). FFA activities promote the development of leadership, collaboration, communication, and teamwork through career development events (Dyer & Osborne, 1995). SAEs provide authentic learning experiences in entrepreneurship, placement, and research-based agricultural projects, supporting career exploration and the development of career readiness skills (Rasty & Anderson, 2025). Each SBAE component can support the integration of STEM knowledge and skills in the learning process. Some examples of how SBAE can serve as a model for integrated STEM education include exploring agricultural ecosystems (i.e., science), using drones and sensors in precision agriculture (i.e., technology), designing irrigation systems (i.e., engineering), or budgeting financial enterprises for SAE projects (i.e., math). While classroom instruction emphasizes formal STEM outcomes, FFA and SAE extend learning beyond the classroom through experiential and out-of-classroom settings. Learning opportunities outside of SBAE could include a robotics club (i.e., FFA parallel) and a science fair (i.e., SAE parallel). Limited research has been conducted to explore how the SBAE program serves as a vehicle for integrated STEM and how SBAE could facilitate integrated STEM learning through the classroom, as well as FFA and SAE components. Because the three-circle model of SBAE and integrated STEM

through AFNR are informed by an integrated approach, we selected systems thinking as a theoretical framework to explore using SBAE as a program model and AFNR as a context for integrated STEM education.

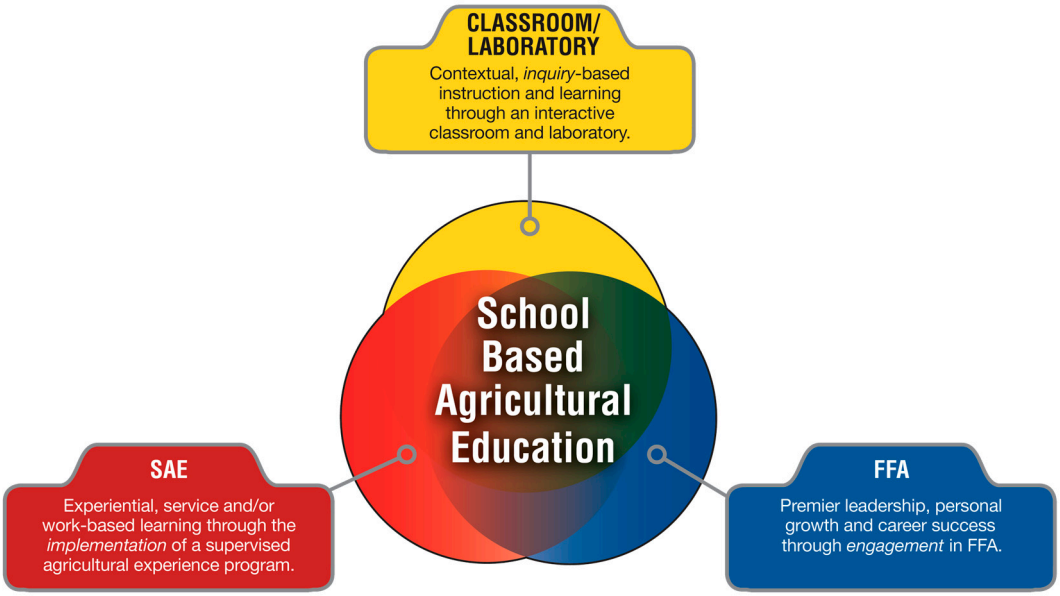


Figure 1. The three-component model for school-based agricultural education. From "What is Agricultural Education," by the (National Council for Agricultural Education, 2025), https://www.thencae.org/what-is-agricultural-education.

2. Theoretical Framework and Literature Review

Over the past two decades, teaching STEM through integrated approaches has gained significant momentum (Johnson & Czerniak, 2023). This reform movement emerged from concerns that the United States was falling behind other nations in preparing a sustainable pipeline of STEM professionals and fostering STEM literacy among all individuals (Schweingruber et al., 2014). Initially rooted in science education, the movement emphasized incorporating engineering design into K–12 science instruction (NGSS Leader States, 2013; Schweingruber et al., 2014). It soon expanded to related disciplines such as mathematics (Maass et al., 2019; Stohlmann, 2019), technology (Asunda, 2014; Wells, 2019), and agriculture (Stubbs & Myers, 2016; McKibben & Murphy, 2021), as well as non-STEM areas such as art (Land, 2013; Danielson et al., 2022), language (Scherer & Azano, 2025; Smit et al., 2023), and law and economics (Kennedy & Odell, 2023). These disciplines increasingly recognize their connection to STEM and their potential to contribute to addressing the needs of society and developing an STEM-literate society and workforce (Kennedy & Odell, 2023). Because STEM focuses on career readiness, state leaders see CTE as an STEM delivery system (Advance CTE, 2013).

AFNR, as a career cluster in the U.S. CTE system, is inherently interdisciplinary (Mulder, 2012), drawing on biology, chemistry, engineering, technology, and mathematics to address complex challenges such as food security, sustainability, and climate resilience. These challenges are deeply interconnected, requiring a systems thinking approach that considers relationships among natural, technological, and social systems to develop holistic and sustainable solutions. Modern agricultural practices increasingly rely on innovations like precision farming, biotechnology, and data analytics, which are advancements that demand strong STEM competencies. Historically viewed as vocational training focused on production agriculture (Barrick, 1989), SBAE has and continues to evolve through significant transformations. Scholars recognize that embedding STEM concepts into agri-

cultural education can foster students' problem-solving and systems-based reasoning skills (Knobloch & Wang, 2024; Warnick et al., 2004). In response, SBAE has reformed its curriculum to emphasize the integration of science and STEM and align with workforce needs. For example, the Curriculum for Agricultural Science Education (CASE) represents the first national effort to embed STEM, particularly science, into SBAE courses (CASE, 2025). Integrated STEM in AFNR has been a focus in SBAE research (Knobloch & Wang, 2024) and practice (Scherer et al., 2019; Wang & Knobloch, 2020; Knobloch & Wang, 2024). This shift reflects a broader call for inclusive and innovative educational models that prepare diverse learners for STEM-related careers while maintaining the unique contextual relevance of agriculture. Building on this shift toward STEM integration in SBAE, we examined the theoretical and conceptual foundations guiding our thinking. We especially framed this conceptual sensemaking paper using systems thinking and integrated STEM to capture the complexity of agricultural education and its interdisciplinary nature.

2.1. Systems Thinking

Systems thinking offers a disciplinary way of knowing for professionals in AFNR, enabling them to navigate and influence complex, interconnected systems (Wang & Knobloch, 2023). As complexity increases across global challenges, systems thinking has emerged as a critical skill (Arnold & Wade, 2015). Systems thinking involves identifying interconnections, recognizing patterns, modeling systems, and predicting the impact of interventions, which are skills essential for sustainable decision-making (Charoenmuang et al., 2024; Meadows, 2008; Ponto & Linder, 2011). A system is defined as a set of interconnected elements working together toward a purpose (Meadows, 2008; Traini et al., 2025). Systems can be found at varying scales; examples of systems in education include a classroom, a local school, the state education system, and the national education system. Systems relate to other systems spatially and temporally; thus, thinking in systems involves adopting increasingly diverse and broad perspectives (Traini et al., 2025).

For integrated STEM through AFNR using SBAE, we adapted a definition of systems thinking that includes four core attributes: (a) seeing a system as a whole as well as its parts; (b) identifying interactions within and across systems; (c) modeling patterns across a system; and (d) proposing interventions and predicting their impact (Arnold & Wade, 2015; Eoyang & Holladay, 2013; Forrester, 1994; Leischow & Milstein, 2006; Meadows, 2008; Ponto & Linder, 2011; Stroh, 2015). Systems thinkers employ synergistic analytical tools and broaden their perspectives across disciplines and beyond traditional academic boundaries (Charoenmuang et al., 2024). AFNR systems are deeply interconnected with other ecological, technological, and social systems. Therefore, systems thinking is essential for advancing sustainability in AFNR. We argue that cultivating systems thinking in AFNR education requires embracing STEM epistemologies and pedagogies to prepare educators and learners for complex problem solving.

2.2. Integrated STEM

We conceptually framed this conceptual sensemaking paper using integrated STEM because it informs the pedagogical approach and strategies to provide cross-disciplinary STEM learning experiences in the context of AFNR. There is no consensus on what integrated STEM is and it has been defined by various researchers in different contexts and disciplines (Knobloch & Wang, 2024; T. J. Moore et al., 2020; Robinson et al., 2018; Scherer et al., 2019). Moreover, some scholars view STEM education as a meta-discipline because it blends disciplinary lines through a problem-driven approach to learning (Kennedy & Odell, 2023). We argue some common themes of integrated STEM through AFNR include (1) solving real-world and contextualized problems; (2) students making authentic con-

nections between academic content they learn in schools and big ideas and cross-cutting themes in the community and world; (3) content integration that is explicitly taught and applied in multidisciplinary, interdisciplinary, and transdisciplinary approaches; (4) integration of two or more content areas that vary by number of disciplines present, extent of integration, and levels of integration; and (5) learner-centered pedagogies that are enacted, which may include active learning, inquiry-based learning, problem-based learning, design-based learning, project-based learning, authentic learning, and contextualized learning. Wang and Knobloch (2023) argued for a more inclusive definition of integrated STEM that would incorporate career and technical education career clusters to help bridge cross-disciplinary learning.

> *Integrated STEM education is intentionally and purposively blending multiple disciplines (i.e., academic and vocational) to help students meaningfully learn and apply academic content through real-world problems framed in designed complex systems and grounded in career and technical contexts that facilitate multidisciplinary, interdisciplinary, or transdisciplinary learning for the development of life-long and workforce development connections and skills*. (Wang & Knobloch, 2023, p. 253)

Knobloch and Wang (2024) framed their definition to show the complementary nature of academic content (i.e., science and mathematics) and career and technical education contexts (i.e., technology and engineering), they specifically argued about how AFNR can serve as an additional CTE context and as a complementary and synergistic context for enhancing integrated STEM that engage students in solving complex real-world problems through systems thinking. Knobloch and Wang (2024) acknowledged some agricultural educators may view integrated STEM as a distraction and not be as focused on vocational education (McKim et al., 2017); however, Knobloch and Wang "argued that integrated STEM makes SBAE more rigorous and relevant for students to be more meaningfully engaged and better prepared to face the challenges in the 21st century workforce and society" (p. 242). As authors, we argue that AFNR and SBAE provide an epistemic value and pedagogical capital that makes STEM learning holistic and relevant to students. This argument is grounded in foundational principles supporting AFNR/SBAE and STEM education, and we framed a literature review conceptually framed on the following: learning by doing, focusing on solving real-world problems, helping students apply content knowledge in out-of-school and community-based settings, enacting learner-centered pedagogies, and developing career readiness skills for the workforce (Robinson et al., 2018).

2.2.1. Learning by Doing

Integrated STEM education and SBAE are informed by a pragmatist philosophy that learning is an active process of applying knowledge and skills to solve real-world problems that are situated in authentic contexts (Coleman et al., 2024; Roberts, 2006). Hands-on learning or learning by doing is a tenet of agricultural education (Knobloch, 2003; Knobloch & Smith, 2024) and STEM education (Robinson et al., 2018). Hands-on learning was the most frequently mentioned instructional strategy in STEM in AFNR from 2010 to 2017 (Scherer et al., 2019). Learning by doing is rooted in John Dewey's philosophy of experiential learning (Roberts & Ball, 2009; Talbert et al., 2022). Common assumptions of learning by doing include the following: knowledge is socially constructed, learning is contextual, learning should develop individuals as life-long learners and workforce professionals, learning knowledge through applications, and experiences are deeply linked with purposeful reflection (Knobloch & Smith, 2024; Roberts & Ball, 2009) and is an effective approach to STEM learning (Lin et al., 2024).

2.2.2. Solving Real-World Problems

Integrated STEM learning experiences are framed and driven by solving problems that simulate real-world contexts and/or grand challenges (Schweingruber et al., 2014; Thibaut et al., 2018). Problems are solved using problem-solving techniques that AFNR and STEM professionals use in the workforce (Jagger, 2023). The problems can be highly structured or be ill-structured. The problem-solving approach to teaching uses highly structured problems and was the most frequently taught teaching method by teacher educators in agricultural education (Ball & Knobloch, 2005). Highly structured problems can include key steps, forked road, possibilities and factors, effect–cause, and situation-to-be-improved. Key steps are the steps to complete a task to solve a problem. A forked road problem has two choices. A problem of possibilities and factors identifies feasible possibilities and each possibility is evaluated using relevant criteria to help make a decision. An effect–cause problem presents effects (e.g., symptoms) and students identify possible causes. A situation-to-be-improved problem is solved by designing a solution to improve the situation after a cause of a problem has been identified (Hedges, 1996; Jagger, 2023). These types of structured problems provide students with patterns so they can recognize common problems efficiently. However, highly structured problems are easier to solve and do not fully prepare students to use critical thinking skills to analyze complexity. In contrast, ill-structured problems in integrated STEM through AFNR (Scherer et al., 2019) are intentionally framed with less structure and detailed information, which is typically presented as complex problems in different stages (Jurdak, 2016). For example, the first stage could provide information about a problem (loosely defined) in a context, which engages students in problem scoping. After identifying different possibilities of what could be the problem, students are presented with additional information in the second stage, which helps them to frame and focus on the problem. After framing and focusing on the problem, students engage in the third stage by identifying the type of problem they are trying to solve and they engage in following one of the five problem-solving techniques listed for structured problems.

2.2.3. Application of Content Knowledge in Out-of-School and Community-Based Settings

SBAE and integrated STEM educators make connections beyond the classroom. AFNR "provides a wealth of context" that is rich in science and technology (Robinson et al., 2018, p. 254). A learning laboratory is an educational environment in education, industry, or a local community that engages students in experiential learning, collaborative teamwork, hands-on skill development and application, and innovative problem-solving. The learning laboratory should be intentionally connected to helping students apply factual knowledge, conceptual knowledge, and procedural knowledge (Krathwohl, 2002). SBAE and integrated STEM educators focus on making content knowledge useful by developing procedural and situational knowledge to help people solve relevant problems (Roberts & Ball, 2009). By learning in educational environments beyond the classroom, learning experiences are enriched with contextualized learning and knowledge (Schweingruber et al., 2014; Murakami et al., 2016). Engaging students to interact and present learning outputs to audiences beyond the classroom raises the stakes for students and helps them better understand expectations and relevant connections to their families and culture, communities of place and identities, and future careers and workforce (Ntaganzwa, 2024).

2.2.4. Learner-Centered Pedagogies

SBAE and integrated STEM educators typically plan and execute learner-centered pedagogies (Stohlmann et al., 2012) to engage students to learn content knowledge and apply content knowledge in learning laboratories to develop procedural knowledge and

learn situational and contextualized knowledge. Learner-centered pedagogies are teaching strategies that are used to engage learners in experiential learning (Coleman et al., 2024) to develop cognitive, career, personal, and community outcomes. Learner-centered teaching is a developmental model (Knobloch, 2021) that stages learner-centered teaching approaches as active learning, inquiry learning, and contextualized learning (Knobloch & Ball, 2006). Active learning focuses on developing critical thinking skills and cognitive outcomes. Inquiry learning focuses on developing problem-solving skills and career readiness outcomes. Contextualized learning focuses on developing and applying knowledge and skills in situations outside of the classroom and developing students' personal and community outcomes.

2.2.5. Development of Career Readiness Skills for the Workforce

SBAE is a vocational education model that engages students to learn knowledge and skills in the cluster of careers in the AFNR industry. Students develop agricultural literacy, knowledge, and skills that prepare students for careers in AFNR (Talbert et al., 2022). Although 20–25% of high school students in agricultural education in the U.S. pursue post-secondary education and careers in AFNR (Junkins, 2000), all students are provided opportunities to learn practical knowledge and skills that can help them be food-system-literate citizens and life-long learners (Thies et al., 2024). STEM education was started to help address workforce needs in the U.S. (NASEM, 2016). The focus was on developing career readiness skills for STEM careers (McDonald & Waite, 2019) and high-quality education and training experiences are needed for all students and those in the U.S. workforce (NASEM, 2016). STEM is important to fields "such as agriculture, energy, environmental science, law and justice, intellectual property, and security, all areas of potential interest to students" (NASEM, 2016, p. 74). Integrated STEM education develops career readiness skills for the STEM workforce (Schweingruber et al., 2014). Because of this, we argued that integrated STEM and SBAE are mutually focused in developing career readiness skills for the workforce (Robinson et al., 2018; Roehrig et al., 2021).

2.3. Linking Theoretical and Conceptual Models

The relationships between systems thinking, integrated STEM, AFNR, and the learning outcomes of career readiness are visually represented in Figure 2. Within the figure, systems thinking permeates both AFNR and STEM which are united by the foundations of learning by doing, addressing real-world problems, application of content, and learner-centered pedagogies. These integrated STEM learning environments provide rich contexts for the development of career readiness skills.

2.4. AFNR as the Integration Catalyst for STEM

Education has been historically divided into specialized domains of knowledge called disciplines (Weingart, 2010). Science and mathematics are foundational academic disciplines (Herschbach, 2011), and technology and engineering are applied disciplines rooted in career and technical (vocational) education. Agriculture thoroughly combines basic and applied STEM disciplines that could be considered STEAM (NRC, 2009) and agriculture for the A in STEM is "a valid context for secondary agricultural sciences education" (Roberts & Ball, 2009, p. 84). Furthermore, the U.S. workforce depends on employees with agricultural and STEM knowledge and skills (Swafford, 2018). Teachers integrate agricultural topics in their instruction because of the way they fit their curriculum; and teachers also see the value of integrating AFNR topics (Knobloch, 2008). Furthermore, educators should integrate ecological, ethical, and social considerations in teaching college students to apply knowledge and solve real-world problems in communities (Odum & Odum, 2001; Orr, 2011). Innovative educational experiences should focus on integrated learning and balanc-

ing the natural capital to meet human needs of food and energy through food production strategy positions of AFNR at the forefront of integrated STEM learning experiences (Odum & Odum, 2001; Orr, 2011).

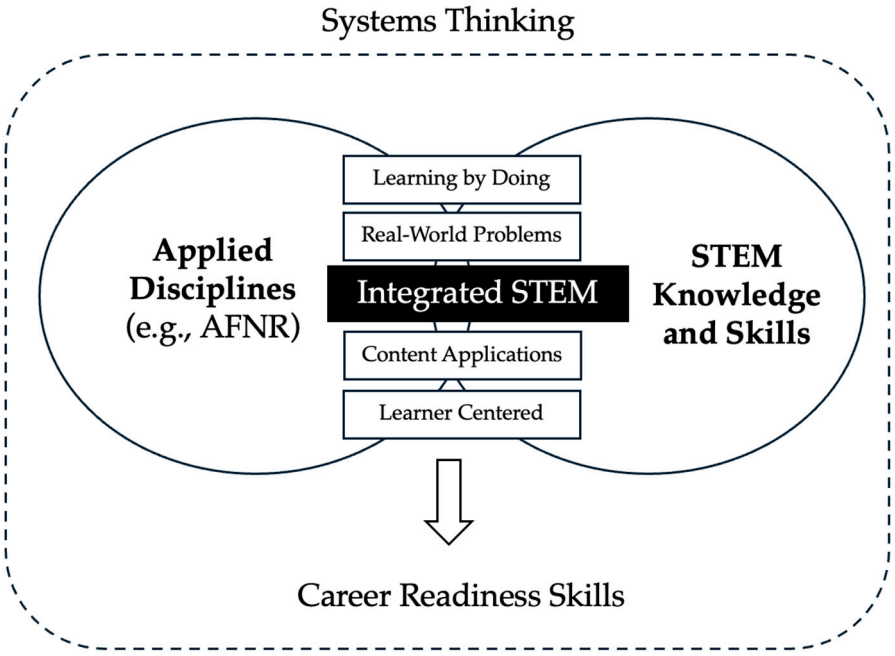


Figure 2. Visualization of conceptual and theoretical linkages.

Integrated STEM is blending disciplines to help students solve authentic problems in meaningful ways that they will do as life-long learners and professionals in the workforce (Schweingruber et al., 2014). Using the push–pull strategy from economics as a metaphor, educators have pushed students to learn academic content with intentions they would apply it in college, careers, and life. Students do not make connections between academic content and the real-world problems they face. Authentic problems are complex, ill-structured, and highly contextualized (Cho et al., 2015). We argue that CTE clusters, such as AFNR, serve as a pull strategy for education. There are several framing considerations of authentic problems so they serve as a pull strategy and drive STEM integration. These consideration include: (1) being aligned with grand challenges, (2) having complexity in knowledge structure is not aligned with single disciplines, but aligned with what professionals in the workforce solve as interdisciplinary and transdisciplinary teams; (3) being aligned with a disciplinary way of knowing, such as scientific inquiry, engineering design, mathematical modeling, and practical systems thinking; and (4) being relevant to students and help them make connections to their culture, communities, and future careers (McLure et al., 2022). Components of authentic learning closely aligned with components of learning STEM through a robotics project, which included scientific inquiry, engineering design, problem-solving, and critical thinking (Barak & Assal, 2018).

It is important to note that career clusters represent industry contexts in CTE and provide meaningful and specific contexts for authentic problems. Career clusters are aligned with industry applications in the workforce and provide students with opportunities to learn procedural and situational knowledge as they apply academic, declarative, and conceptual knowledge in real-world contexts. Specifically and pedagogically, AFNR is more than a context; AFNR is a pull strategy that engages students to solve complex problems that will help people live healthy and sustainable lives. AFNR provides a unifying integration of content to solve authentic problem-solving in community-based contexts as people use local resources for their food and energy as they struggle to find a balance to live sustainably with

nature. AFNR not only provides context, but it provides purpose-driven complex problems, which becomes the catalyst for integrated STEM, interdisciplinary and transdisciplinary learning, practical systems thinking that helps people live healthy and sustainable lives, and balancing the tensions of doing so with nature. There is limited research and models that support how CTE clusters serve as catalyzing integrators to synergize integrated STEM education. To address the gap in the literature to better understand the potential for STEM learning within educational contexts like AFNR as a foundation, we aimed to advance integrated, interdisciplinary learning by conceptualizing model approaches for empowering educators to facilitate STEM learning within their diverse educational spaces.

3. Methods and Analysis

As agricultural STEM educators, we engaged in collaborative sensemaking to understand and make sense of our own experiences as teacher educators and scholars regarding what would be an ideal model, approach, or conceptualization to help develop pre-service and in-service teachers to plan, implement, and assess integrated STEM through AFNR. The following research question guided us to engage in this sensemaking process: based on your experiences as a teacher educator and scholar, what would be ideal to help develop pre-service and in-service teachers to plan, implement, and assess integrated STEM through AFNR?

Kelley and Knowles (2016) recommended STEM teacher educators to clarify conceptual understanding of integrated STEM education "by teaching key learning theories, pedagogical approaches, and building awareness of research results of current secondary STEM educational initiatives" (p. 10), which supported why we developed this conceptual paper. Individual and collaborative reflections on our scholarship and professional practices served as data sources. As faculty at U.S. land-grant universities engaged in teaching, research, and engagement of integrated STEM through AFNR, we collaboratively engaged in six sensemaking conversations to individually and collectively explore our conceptual knowledge of how integrated STEM plays a role in the context of AFNR and SBAE. Although it may seem that SBAE and AFNR are interchangeable, we used these two terms with specificity. SBAE is an educational program model where certified teachers teach secondary students' content, procedural, and contextual knowledge of the career cluster and curriculum of AFNR. The agriculture teacher also helps build career readiness skills by facilitating experiences beyond the classroom to help students apply knowledge and develop skills regarding the content they learned in their classes, and students learn leadership skills through career development events and FFA chapter activities. As authors, we have professional experiences in teaching secondary students in SBAE and prepared pre-service teachers to engage in teaching AFNR in formal and non-formal educational settings.

To develop this conceptual paper, we chose sensemaking as a method of scholarly engagement and collective reflection because it is aligned with Dewey's pragmatic approach to reflection and making sense of various experiences to inform our conceptual understandings and enactments as engaged scholars and teacher educators (Weick, 2020). "Sensemaking involves the ongoing retrospective development of plausible images that rationalize what people are doing" (Weick et al., 2009, p. 163). Sensemaking is especially useful in thinking deeply about real-world experiences, interrogating them with existing knowledge and concepts, creating new conceptions, and adapting knowledge, strategies, and conceptual models while evolving in the usage and application of ideas and concepts. This is particularly useful for integrated STEM in AFNR and SBAE as it is being implemented, defined, conceptualized, empirically tested, and modified as a relatively new phenomenon in career and technical education.

As authors, we worked through three stages of sensemaking. First, we identified words and key constructs based on our organizational circumstances. Authors were from three different universities and we thought about our individual experiences in these contexts and shared our reflections with each other. Two authors focused on the teacher certification requirements and how they prepare pre-service teachers and two authors focused on the cognitive and planning processes of integrated STEM, which was informed by formal and non-formal education contexts. Second, we organized our thoughts from our experiences into narratives that provided meaning and contextualized knowledge. One author explained the process model of SBAE. Another author explained the construct and process of systems thinking. Another author explained the compatibility and benefits of AFNR as a means to teach integrated STEM. For the third stage, the authors conceptualized the "invisible hand" and provided a concrete representation of how integrated STEM would be ideally operationalized in higher education institutions, as informed by their professional experiences in their universities. Authors used a cognitive and social analytical framework. They prepared a written narrative reflecting on their professional teaching and scholarly research experiences and the practicality of strategies working in their present situations, explained them in the collaborative discussions, provided additional explanations, and received feedback from other authors so each author could move forward and work on their models and sections based on the collaborative sensemaking process. Because the authors reflected on their own professional experiences and scholarly outputs and outcomes through the sensemaking process, we wrote positionality statements to disclose our subjective identities, backgrounds, and perspectives of integrated STEM and SBAE. We acknowledge that the use of citations of our work served as documentation of our scholarship and supporting evidence for the sensemaking results.

Author-1 is a professor of Agricultural STEM Education who taught middle and high school students agricultural science and business prior to pursuing their doctoral degree in teacher education. Author-1's teaching and research focuses on student motivation, theorizing, research design, and teaching integrated STEM using agriculture, food, and natural resources as a context and integration strategy. They co-teach a teaching method course on integrating STEM through AFNR with Author-4. Professional development modules on how to integrate STEM through AFNR have been developed and they have engaged rural and urban STEM and agriculture teachers to engage high school students in food system STEM projects. They co-authored several journal articles and book chapters on integrated STEM in the context of AFNR.

Author-2 is an associate professor of agricultural education who served as a middle and high school agriscience teacher prior to entering academia. Author-2's teaching and research focuses on inquiry-based instruction and STEM integration. They teach a course on inquiry-based instruction and STEM integration at the undergraduate level for pre-service agricultural education teachers. Author-2's research aims to improve agricultural education teacher preparation through purposeful STEM integration and the development of effective teaching characteristics.

Author-3 is an associate professor within the AFNR Education program in the Department of Community Sustainability at Michigan State University (MSU). Before pursuing graduate work, Author-3 taught middle school and high school AFNR courses in [state]. As a faculty member, Author-3's scholarship explores the essential role of educators in providing STEM, AFNR, and leadership learning experiences. This interdisciplinary emphasis is embedded in the courses taught by Author-3 at [university], wherein they seek to empower pre-service educators to plan, implement, and evaluate integrated STEM learning within AFNR classrooms. Author-3's emphasis on integrated STEM learning can also be found in their work on land-based learning, a pedagogical approach they co-developed through

grants and scholarship which positions secondary school learners within interdisciplinary teams to address authentic sustainability challenges in their local community.

Author-4 is an associate professor with joint appointments in the [department] and [department]. Their research centers on defining and exploring integrated STEM instruction through AFNR, working closely with secondary STEM and agriculture educators. Their work spans both formal and non-formal educational settings. In addition to co-teaching a course with Author-1, they also co-teach methods of integrated STEM education for secondary STEM educators with other faculty. They have co-authored several journal articles and book chapters on integrated STEM in the context of AFNR.

4. Findings, Discussion, and Limitations

We engaged in independent reflections and six conversations. We reflected on our experiences as teacher educators and scholars through four steps: (1) engaged in sensemaking to collectively generate and think deeply about our real-world experiences; (2) interrogated our experiences with existing knowledge and concepts of integrated STEM and the disciplinary assumptions of SBAE and AFNR; (3) created new conceptions and adapted knowledge, strategies, and conceptual models; and (4) developed strategies and approaches to help pre-service and in-service teachers plan, implement, and assess integrated STEM through AFNR. We developed a three-model framework to focus and frame integrated STEM through AFNR and used the SBAE program as the context and means of instructional engagement.

4.1. Teacher Model for Integrated STEM in SBAE

The teacher model brings to the forefront the educator's role in facilitating integrated STEM learning. Educators are the gatekeepers to their curriculum (McKim et al., 2017) and they need support and development to teach integrated STEM (K. Moore & Yulianti, 2014). Thus, identifying the skills and dispositions among educators, which supports their facilitation of integrated STEM learning is critical. In our model (Figure 3), three essential educator attributes are proposed: (a) motivation, (b) competence, and (c) margin.

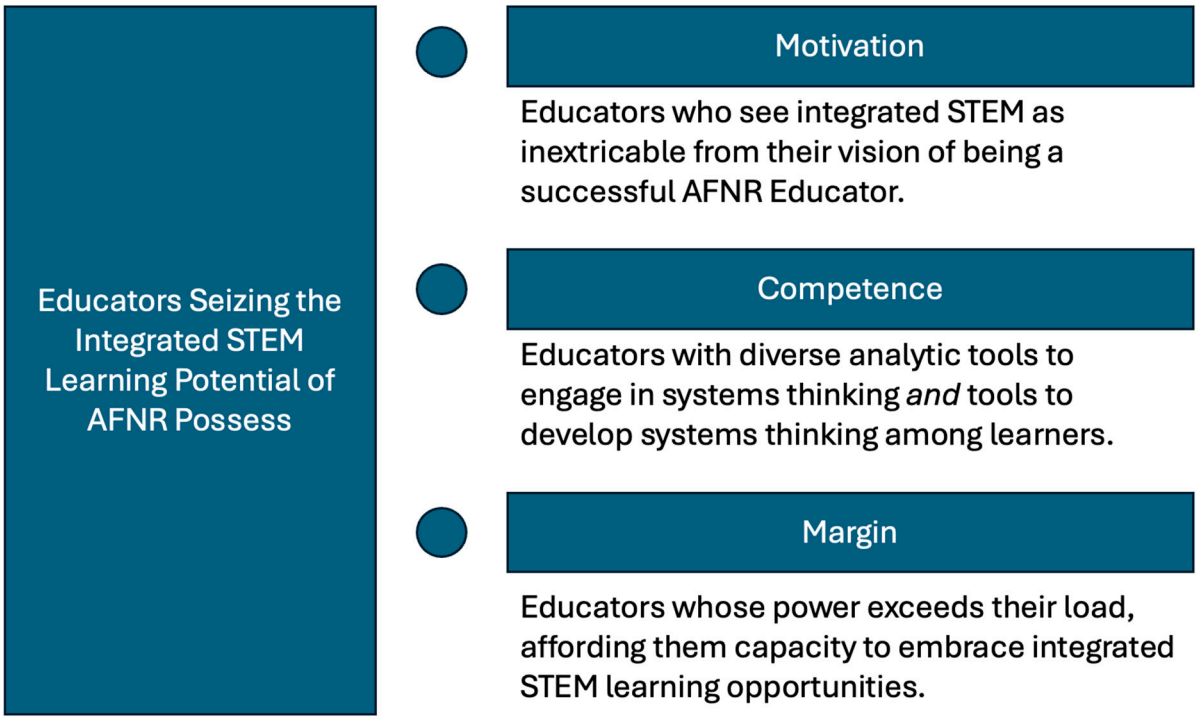


Figure 3. Teacher model for integrated STEM in AFNR.

The motivation required among educators to facilitate integrated STEM learning within AFNR is defined as educators who see integrated STEM as inextricable from their vision of being a successful AFNR educator. This attribute highlights that educators who foster integrated STEM learning acknowledge the importance of these learning experiences, viewing them as a required element of facilitating AFNR instruction. The competence attribute acknowledges motivation alone will not yield successful integrated STEM learning. In the teacher model, competence is defined as educators with diverse analytic tools to engage in systems thinking and tools to develop systems thinking among learners. This attribute highlights systems thinking as a way of knowing necessary for engaging in integrated STEM learning in AFNR. Additionally, this attribute implies educators utilize systems thinking themselves as well as possess the ability to develop systems thinking among learners. The final attribute within the teacher model is margin. Teacher margin is the difference between a teacher's load (i.e., collection of all required tasks) and power (i.e., internal and external resources accessible to accomplish tasks) at any given time (McKim & McKim, 2023). Having margin as an educator is essential; available resources are required to seize emerging opportunities and solve emerging challenges as a teacher (McKim & McKim, 2023). Within the model, margin is defined as educators whose power exceeds their load, affording them capacity to embrace integrated STEM learning opportunities.

This model was developed and applied throughout the AFNR Education program by Author-3 at [university]. Pre-service teachers within the AFNR teacher education program earn teaching credentials in both AFNR and biology. This approach yields a blend of science and AFNR coursework throughout their degree program. This foundational knowledge is built upon in their degree program, with students being introduced to technology, engineering, and mathematics ways of knowing and their connections to AFNR systems. These interventions are designed to increase the pre-service educator's motivation to teach integrated STEM. Competence is built among pre-service teachers in the Michigan State University AFNR education program through system modeling courses. Students in the program are required to take two courses which focus on developing knowledge and confidence modeling complex social–ecological systems. This foundation of knowledge is built upon within the program as students translate their own ability to model complex systems into structured learning experiences for their future students. Finally, teacher margin is a central component of the AFNR education program at [university]. Pre-service teachers are introduced to the concept of teacher margin early in the program through the Donut Model for Teacher Success (McKim et al., 2024). This model empowers students to interrogate their own definitions of AFNR educator success, often replacing notions which would limit margins with more boundary-infused, margin-supported visions. This reconceptualization of success then informs pre-service teacher engagement with the profession, including early-field experiences and student teaching, wherein they are encouraged to engage with programs that illustrate both success and teacher margin.

4.2. Program Model for Integrated STEM in SBAE

The program highlights the intercurricular nature of SBAE and the opportunities for integrated STEM learning outcomes across the three-component model (Swafford, 2017), all of which are grounded in a systems thinking approach (see Figure 4). FFA and SAE activities that are tied to classroom instruction and grading makes these components of the three-component SBAE model intracurricular. Within the classroom and laboratory component of the program, STEM knowledge and skills are taught within the given context (e.g., agriculture, food, and natural resources), which then connects to the FFA leadership development component with an application of STEM learning and the SAE component with opportunities for students to apply what they have learned through personalized

STEM projects. The FFA component serves as a vessel for STEM in leadership, collaboration, and communication, which can be further expanded and connected to SAE opportunities through STEM career development experiences. SAE affords students the opportunity to apply STEM concepts in experiential settings. Together, these three components result in the ideal program model, offering integrated STEM through AFNR (Swafford, 2017).

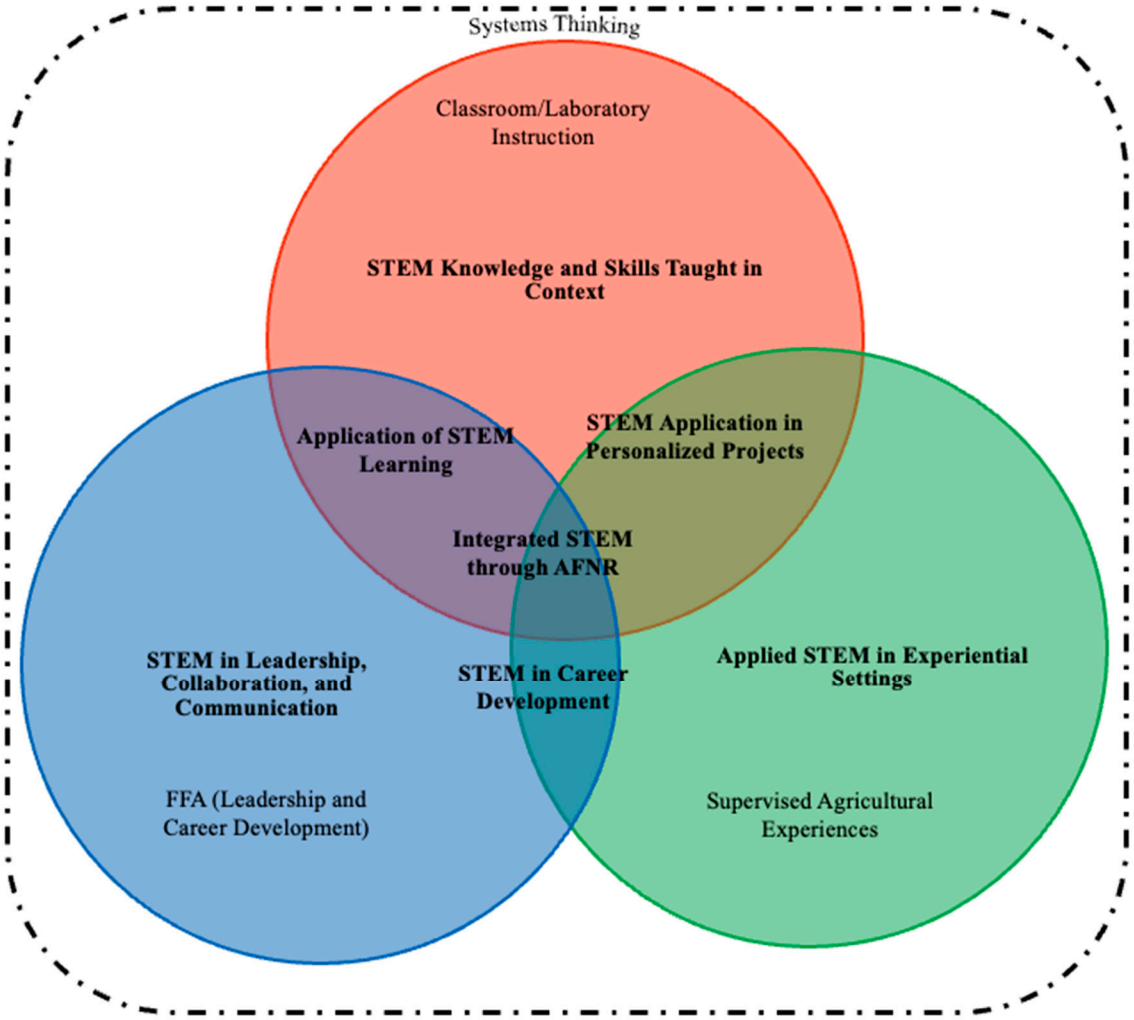


Figure 4. Three-circle Program model for integrated STEM in SBAE.

The comprehensive SBAE program serves as the "system" being considered, providing SBAE teachers with a vessel to engage students in addressing real-world problems through practical solutions, ultimately advancing our world (Ponto & Linder, 2011). Specifically, an example of this within the application of STEM learning would be a student in a greenhouse management course learning about environmental control systems, which then leads to an opportunity coordinating the FFA community plant sale, applying STEM knowledge to real-world production and marketing challenges. Similarly with STEM application in personalized projects, an animal science student applies statistical methods learned in class to analyze weight gain trends and optimize feed rations for their livestock SAE project, aligning to student interests and providing an opportunity to apply STEM contexts within students' unique contexts. Finally, an example of STEM in career development could be a student who is interested in pursuing a career in veterinary medicine who has a placement SAE working at a veterinary clinic, which leads to developing and delivering a prepared public speech at an FFA leadership development event on STEM-based animal health

practices, ultimately preparing the student for college and career readiness in their area of interest.

Within pre-service SBAE teacher preparation, highlighting this "ideal" program model for integrated STEM can be challenging. This model was developed and tested by Author-2 at Oklahoma State University. Within the agricultural education program at Oklahoma State University, students engage in purposeful early-field experiences tailored to highlight these integral components (i.e., classroom/laboratory instruction in red, FFA in blue, and SAE in green). These include 60 hours of prescribed experiences with SBAE teachers and in SBAE programs across the state. Programs that are selected can provide opportunities for students to see all three components of the comprehensive model for agricultural education. One specific example is within an inquiry-based teaching methods course, which focuses on integrated STEM, which entails pre-service teachers engaging in a one-day experience in a four-teacher SBAE program that provides opportunities for observation and engagement in foundational systems, animal systems, plant systems, and power, structural, and technical systems. This immersive experience allows pre-service teachers to see the application of course concepts, inquire about best practices from SBAE teachers, and begin to form their integrated STEM identity as an SBAE pre-service teacher.

4.3. Learning Process Model for Integrated STEM Through AFNR

The learning process model (see Figure 5) for teaching integrated STEM through AFNR has three steps. Step 1 begins with framing a food system challenge in the context of AFNR. Food system challenges are aligned with wicked problems (Skaburskis, 2008) such as food insecurity, climate change, food waste, energy conservation, or renewability and environmental sustainability (Batie, 2008). Food system challenges help students make local connections to complex problems known as grand challenges, which aligns with Kennedy and Odell's (2014) recommendation to engage students to learn STEM using multiple perspectives that cross local and global boundaries. Grand challenges are complex, uncertain, and evaluative (i.e., driven by human values; Ferraro et al., 2015). Food system challenges provide contextualized learning experiences that are complex and ill-structured (Lönngren & Poeck, 2020) to facilitate systems thinking and cross-disciplinary learning (i.e., interdisciplinary or transdisciplinary; Pohl & Hadorn, 2008; Worosz, 2022) that help students apply science, technology/engineering, and mathematics to solve the complex problem (Zellner & Campbell, 2015).

Step 2 is to intentionally design integrated STEM learning experiences by framing the problem using pragmatic systems thinking (Whyte & Thompson, 2011). Integrated STEM learning blends content areas as students solve authentic, complex problems (Lake, 2015; Roehrig et al., 2021). Food system STEM challenges are framed with a disciplinary way of knowing that helps guide integrated STEM learning and develop solutions (Ferraro et al., 2015). The complexity of the food system problem is given structure by framing them using one of the S, T/E, or M ways of knowing—scientific inquiry, design-based thinking, or mathematical modeling. This pedagogical approach aligns with teachers who were more efficacious in implementing project-based learning and demonstrated more capacities to teach integrated STEM (K. Moore & Yulianti, 2014; Mustafa et al., 2016).

For Step 3, students engage in systems thinking by evaluating their proposed solutions based on four factors: (1) production efficiency; (2) economic viability; (3) environmental sustainability; and (4) social responsibility (Agunga et al., 2005; Pohl & Hadorn, 2008). Pragmatic systems thinking is used to solve food system challenges and this is particularly important to consider the trade-offs of meeting human needs (Ferraro et al., 2015; Murakami et al., 2016) by growing food and energy that align with consumer values (i.e., social responsibility) and being most environmentally sustainable (Hoffman et al., 2021; Lake,

2015). Pragmatic systems thinking is used to frame solutions by evaluating food systems components for the purpose of improving the system (i.e., production efficiency, economic viability, environmental sustainability, and social responsibility) through the following ways: (a) seeing a system as a whole as well as its parts; (b) identifying interactions within and across systems; (c) modeling patterns across a system; and (d) proposing interventions and predicting their impact (Arnold & Wade, 2015; Eoyang & Holladay, 2013; Forrester, 1994; Leischow & Milstein, 2006; Meadows, 2008; Ponto & Linder, 2011; Stroh, 2015). Although all four purposes can be considered collectively, the decision-maker will need to prioritize which system factors align with their values and what would contribute to the most pragmatic system solution (Murakami et al., 2016; Pohl & Hadorn, 2008; Traini et al., 2025). Ultimately, the goal is to make learning relevant and provide opportunities for students to apply science and mathematics that are meaningful in their own lives (Kennedy & Odell, 2014).

The learning process model was developed and implemented through planning multiple lessons that build on each other to provide students with integrated STEM learning experiences using complex problems in an AFNR context by Author-1 and Author-4 at [university]. Robinson et al. (2018) advocated for "purposeful planning and intentional instruction, whereby students will benefit from having well-developed 21st century skills by engaging in opportunities to practice and sharpen these skills both in and out of the classroom" (p. 258). The learning process model of integrated STEM through AFNR is based on five assumptions: (1) be planned for intentional cross-disciplinary learning; (2) be driven by complex problems that are aligned with local and global challenges; (3) be contextualized by agriculture, food, and natural resources; (4) engage students in practical systems thinking that includes production efficiency, economic viability, environmental sustainability, and social responsibility; and (5) engage students in multisensory learning experiences using learner-centered pedagogies (i.e., active learning, inquiry learning, contextualized learning).

Wang and Knobloch (2020) outlined the planning process they used to help students develop mini-unit examples, which consisted of three to five lessons (~45 min per lesson) in a three-credit undergraduate and graduate course at [university]. The instructors framed this innovative course as interdisciplinary learning for the development of integrated STEM through AFNR lessons after learning about the nature of S, T, E, M as single disciplines. Then, students learned to integrate AFNR into STEM using AFNR as the driver of integrated learning and systems thinking. The instructors introduced five teaching methods (i.e., learner-centered teaching, inquiry-based teaching, engineering design, mathematical modeling, and culturally relevant teaching). Pre-service teachers had freedom to develop their STEM-integrated lesson plans by using what they believed would be the most appropriate integrated model based on the food systems challenge and how it could be framed for integrated STEM learning and systems thinking. Pre-service teachers developed their lessons using a rubric that identifies criteria, levels, and evidences of integrated STEM through AFNR (Wang & Knobloch, 2022). They found that pre-service educators were able to accurately interpret three components using the rubric: "(1) applying STEM content to solve real-world problems; (2) making cross-disciplinary connections; and (3) using learner-centered teaching strategies to promote critical and deeper thinking" (p. 20).

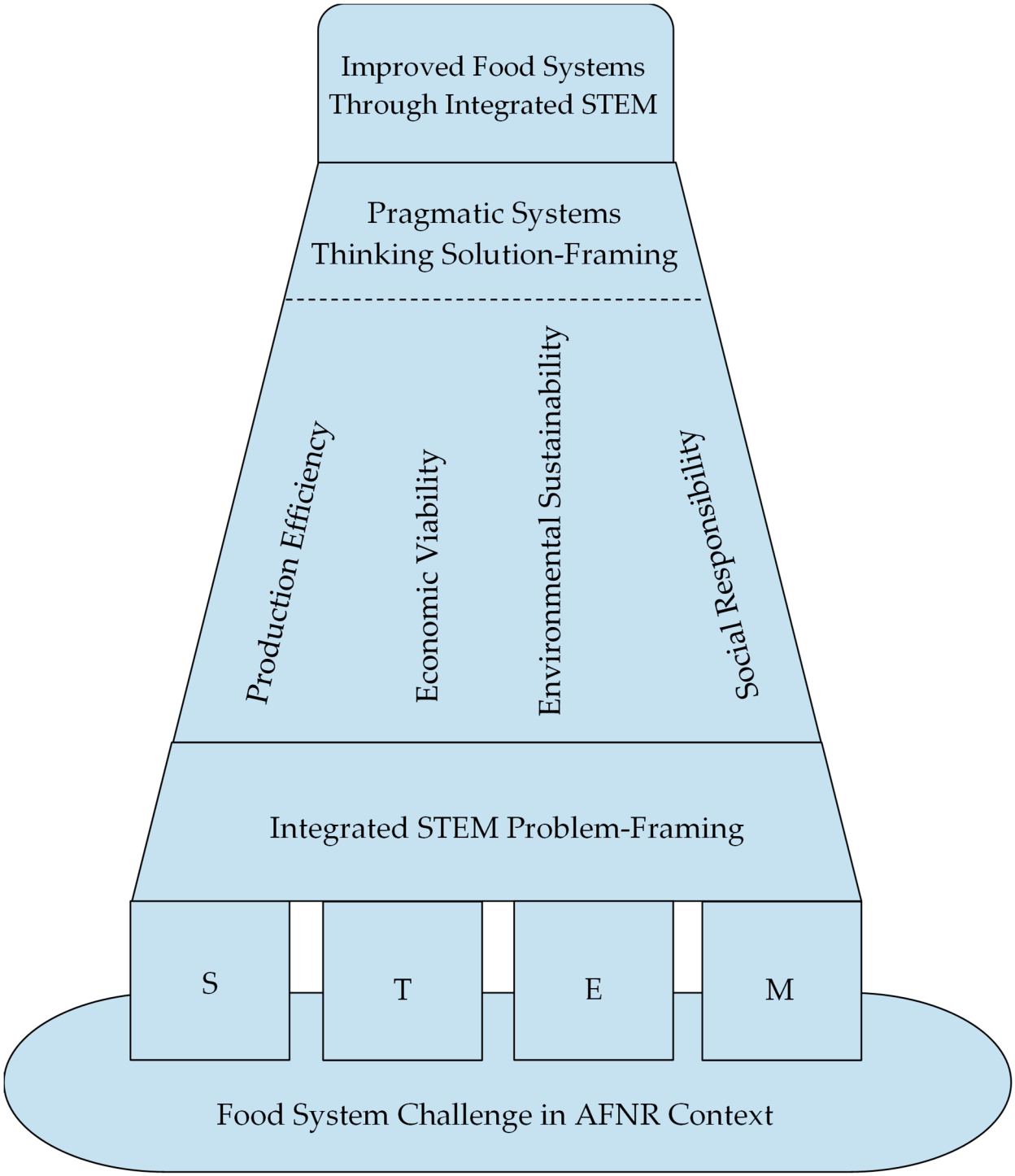


Figure 5. Learning process model for integrated STEM through AFNR.

4.4. Conceptual Diagram Linking the Models

Bringing the models together (see Figure 6) illuminates the interconnected nature of our sensemaking. When motivated, competent, and possessing margin (see Figure 3), educators are positioned as catalysts to facilitate integrated STEM learning across all three components of the SBAE program. This potential is realized when educators facilitate the integrated STEM learning process (see Figure 5) within diverse, STEM-rich program components (see Figure 4). The interaction of the STEM learning process and program components unite learner engagement in systems thinking when addressing authentic problems.

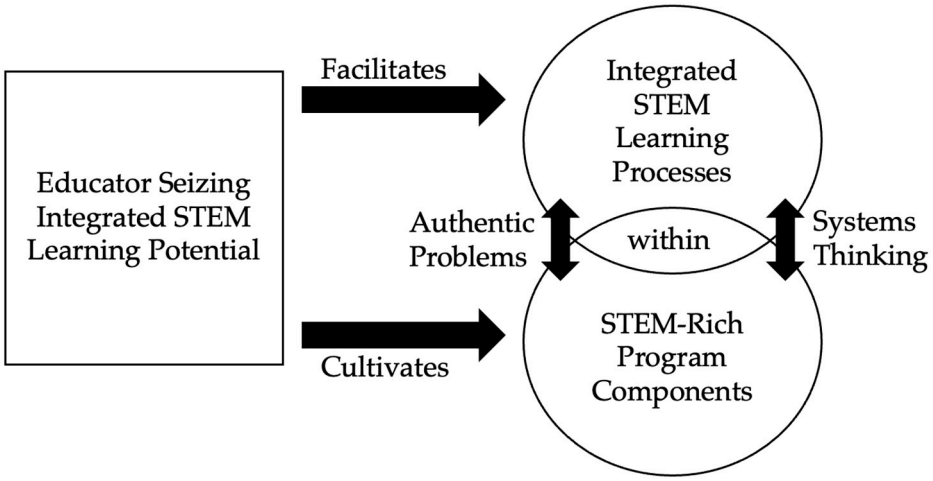


Figure 6. Conceptual diagram linking teacher, program, and learning process.

5. Implications for Career and Technical Education

As authors, we went through a collective sensemaking process to develop this conceptual article. We reflected on our practical experiences in engaging pre-service and in-service teachers to demonstrate how SBAE teacher educators and teachers can implement integrated STEM through AFNR. We acknowledge our focus on developing teachers, integrating STEM in SBAE programs, and intentionally designing and implementing integrated STEM learning using food system challenges were limited to our professional and scholarly experiences. As we reflect on the three-model framework, we envision they can serve as models of integrating STEM in other CTE clusters such as (1) advanced manufacturing; (2) construction; (3) supply chain and transportation; (4) arts, entertainment, and design; (5) hospitality, events, and tourism; (6) financial services; (7) education; (8) health career and human services; (9) public service and safety; (10) energy and natural resources; (11) digital technology; (12) marketing and sales; (13) management and entrepreneurship (Advance CTE, 2024). CTE is more academically focused than vocational education and has been included in STEM content in CTE curricula (Schweingruber et al., 2014).

5.1. Teacher Model Applied to Broader CTE

The proposed teacher model, featuring the three attributes of an educator prepared to seize integrated STEM learning opportunities, may be applicable across CTE clusters. Teachers' beliefs, understandings, and challenges of integrated STEM education should be considered for integrated STEM education to be implemented as a sustainable program (Han et al., 2022; Ryu et al., 2018). Regardless of cluster, educators identifying integrated STEM learning as inextricable from their success will support their integration of STEM skills and knowledge within their curriculum. When held by teachers, this perspective provides the motivation necessary to foster integrated STEM learning within their curriculum. Additionally, the systems thinking competence detailed within the teacher model supports any CTE educator fostering integrated STEM learning. The universal nature of this attribute speaks to our contention that integrated STEM learning and systems thinking are intertwined; inherently, fostering integrated STEM learning requires the educator to engage multiple systems of knowledge. Therefore, facilitating integrated STEM learning is engaging in systems thinking as an educator alongside engaging learners in systems thinking. We also acknowledge the importance of implementing integrated STEM with system considerations of the community, school administration, curricula, and the support of professional development and a community of practice (Han et al., 2022; Kelley et al., 2020). Finally, teacher margin also positions educators to facilitate integrated STEM learning. As

the program and learning process models highlight, integrated STEM learning is enhanced through authentic problems and diverse learning contexts. Seizing emerging opportunities to expand learning in these ways requires teacher margin. The teacher model for integrated STEM in SBAE has several boundary conditions and potential limitations. The model assumes teachers have curricular autonomy and can make choices regarding how they spend their time and instructional activities, both in and outside of the classroom. If the teacher is in a context where they are mandated to teach a prescribed curriculum in a prescribed way, the model would be less applicable. Moreover, some teachers may not have enough professional experiences and feel competent in their abilities to accurately define success. Some teachers may have unrealistic expectations based on their own expectations and the expectations of their students, parents, administrators, and community stakeholders. Some teachers may be constrained by traditional expectations that may restrict innovative teaching strategies and curriculum that would promote integrated STEM. The complexity of teaching systems thinking, complex challenges, and integrated STEM may serve as barriers for some teachers to effectively apply the teacher program model for integrated STEM in SBAE.

5.2. Program Model Applied to Broader CTE

Integrated STEM learning should be promoted in diverse settings (e.g., work-based learning, CTSO, classroom/laboratory) within the career clusters that are relevant to students (McLure et al., 2022). The connections between these diverse settings are equally important to promote the cross-disciplinary nature of integrated STEM. As teachers consider how to establish an integrated STEM program within their discipline, it is essential to consider the classroom learning environment, the opportunity for student engagement through a Career and Technical Student Organization (CTSO) or community-based youth organization, and non-formal educational experiences. Purposeful student development and engagement in classroom/laboratory instruction and a CTSO or community-based youth organization results in collaborative applications of STEM in your school and community. Similarly, engaging students in individualized projects and other non-formal educational experiences in addition to structured classroom/laboratory instruction provides an opportunity for individualized application of STEM. Finally, the crossover between these individualized projects and CTSOs provides a culminating experience for students with career readiness through STEM-based experiences. It should be noted that this model identifies an ideal program within the AFNR context, and actual program implementation may vary based on specific needs of the teacher, students, school, and community. The program model for integrated STEM in SBAE has several boundary conditions and potential limitations. The program model assumes three components that include career readiness activities that occur outside the classroom but are connected to the curriculum and learning assessments. Specifically within the program model, integrated STEM lies within the overlap between classroom/laboratory instruction, FFA, and SAE (see Figure 3), which is not always obtainable, especially in contexts outside of AFNR, as many students are enrolled in CTE programs but not actively engaged in the corresponding CTSO. Some teachers struggle with teacher margin in adequately balancing the three components of instruction, FFA, and SAE activities. Moreover, the additional teaching load of teaching ill-structured authentic problems, systems thinkings, and integrated STEM adds complexities to the program model. Some students may choose not to engage in out-of-classroom career readiness activities or may not have the resources to do so (e.g., transportation; parent support). The programmatic model is considered an ideal model for integrated learning to develop career readiness skills. Teachers will need to consider their margin in implementing the model to meet the needs of their students through purposeful implementation.

5.3. Learning Process Model Applied to Broader CTE

Integrated STEM learning emerges from authentic, contextually relevant problems/challenges, which can help students apply socioscientific reasoning (Öztürk & Roehrig, 2024). Embedding integrated STEM within these challenges helps promote authenticity and applicability to the systems thinking. This model should be adapted to other CTE career clusters by framing problems and challenges in other industry contexts (e.g., health and human services). For example, there are many complex, ill-structured problems and industry challenges in medicine. Subramaniam et al. (2024) identified global challenges in medical engineering as engineering genomes and cells, accumedicine, smart devices for human function augmentation and neuropathologies, and approaches to harness the human immune system for health and wellness. Specifically, a medical system challenge could engage students to design a smart device to help people with Alzheimer's disease function more effectively in physical applications. Framing integrated STEM problems that require systems thinking solutions and are meaningful to students (McLure et al., 2022) will help develop life and career readiness problem-solving skills in authentic settings that will improve the quality of life of people. The learning process model for integrated STEM in SBAE has several boundary conditions and potential limitations. First, teachers need specific training and coaching to effectively implement the learning process model and facilitate learning for students to understand STEM and AFNR ways of knowing. The learning process model is driven by a focused and framed authentic, complex problem. Problem scoping, framing, and solving can be difficult and time-consuming to develop. Furthermore, teachers need STEM and AFNR subject-matter expertise to plan, facilitate, and evaluate integrated STEM through AFNR.

6. Conclusions and Future Directions for Research

The proposed three-model framework—Teacher, Program, Learning Process (TPLP)—offers a systems thinking foundation to conceptualize and implement integrated STEM instruction through AFNR within SBAE. This three-model TPLP framework responds to Swafford's (2018) recommendation to help SBAE teachers implement integrated STEM into their programs without creating "AgriSTEM fatigue" (p. 328) with structured approaches to integrate STEM through AFNR because they can be integrated into the SBAE program. Moreover, the three-model TPLP framework directly addresses the current literature, which reflects growing recognition of the value of STEM integration in SBAE, yet also reveals persistent gaps in implementation, conceptual clarity, and research depth. Studies consistently show that educators perceive STEM integration as important (Norris et al., 2024; Smith et al., 2015), and that science and technology are more frequently embedded in SBAE instruction than engineering and mathematics (Eck et al., 2020; Stubbs & Myers, 2015). These findings suggest that teachers often lack confidence and competence in integrating STEM subjects, particularly engineering and mathematics.

The Teacher Model supports professional development by identifying three key educator attributes, namely motivation, competence, and margin, that influence STEM integration. Motivation reflects an educator's belief that STEM is essential to effective AFNR instruction. Competence involves the ability to engage in and foster systems thinking across disciplines. Margin refers to the educator's capacity to embrace emerging STEM opportunities, where available resources exceed instructional demands. Building on this model, future scholarly endeavors can explore how these attributes shape educator identity, instructional decision-making, and professional growth over time.

On the other hand, the Program Model aligns SBAE's tripartite structure (i.e., classroom/laboratory, FFA, SAE) to provide a holistic framework for developing agriculture-based STEM programs (Swafford, 2017). While some research has examined high school

agriculture programs (e.g., McKim et al., 2025; Stubbs & Myers, 2015, 2016), these studies have primarily focused on teacher perceptions and instructional methods. Limited research has explored how all the components of the SBAE model are operationalized to support integrated STEM learning in K-12 public schools. Moreover, few studies have investigated instructional design, student outcomes, or the epistemological foundations of STEM within AFNR contexts (Knobloch & Wang, 2024). One contributing cause is lack of a comprehensive framework that offers a clear pedagogical roadmap for delivering integrated STEM instruction through complex real-world challenges. Student autonomy and choice play an important role in selecting and framing authentic problems to design STEM-based solutions (McLure et al., 2022).

The Learning Process Model addresses this need by emphasizing intentional planning, contextualization, and systems thinking. It provides a practical guide for instructional designers and researchers to explore how students engage with interdisciplinary problem-solving and how teachers facilitate meaningful STEM learning. This model encourages the use of learner-centered pedagogies, such as inquiry-based and contextualized learning, and frames instruction around food system challenges that reflect global and local issues. While this article focuses on a U.S. context for integrated STEM given the nature of school-based agricultural education, educators across the world have the opportunity to apply concepts and best practices for integrated STEM and systems thinking within their educational systems using strategies to develop career readiness skills. Educators in other countries can adapt this model by focusing on integrated learning experiences that engage students in interdisciplinary learning for academic and career readiness (e.g., leadership; workplace skills).

Researchers can apply the three-model TPCP framework to examine how teachers design integrated STEM units and use teacher margin in implementing integrated STEM lessons, how teachers facilitate integrated STEM through AFNR in SBAE, and create STEM career readiness activities using the SBAE program. We recommend researchers use the TPCP framework to identify new ways to integrate STEM through various CTE career clusters and program models, how students develop systems thinking, and how partnerships across agricultural education, STEM disciplines, and educational psychology can lead to new theoretical models, instructional tools, and policy innovations. By grounding future scholarship in systems thinking and the operational models presented in this paper, researchers and practitioners can move beyond fragmented efforts toward a cohesive, transformative vision for integrated STEM in SBAE.

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Abbreviations

The following abbreviations are used in this manuscript:

AFNR	Agriculture, Food and Natural Resources
CTE	Career and Technical Education
CTSO	Career and Technical Student Organization
SBAE	School-based Agricultural Education
STEM	Science, Technology, Engineering, and Mathematics
TPCP	Teacher, Program, and Learning Process

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