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STEM-Based Deep Learning in Food Security Education for Sustainable Development Goals: A Systematic Review of Scientific Literacy and Self-Efficacy

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Abstract: This study aims to synthesize research on STEM-based deep or meaningful learning in food security and sustainability education, with a particular focus on its relationship with scientific literacy and self-efficacy. A systematic literature review was conducted using the PRISMA 2020 framework across Scopus, ERIC, Google Scholar, and SINTA-indexed sources. The screening process resulted in nine core studies that met the predefined inclusion criteria. The findings reveal that existing research is structurally fragmented across three domains: contextual STEM learning, pedagogical processes, and cognitive–affective outcomes. While STEM-based learning is widely applied in sustainability contexts, food security is predominantly treated as a thematic background rather than an epistemic learning domain. Furthermore, scientific literacy and self-efficacy are typically examined as separate constructs, limiting the understanding of how cognitive and affective dimensions interact in learning processes. In response to these gaps, this study proposes an integrative framework that connects food security as an epistemic context, STEM as an interdisciplinary structure, deep learning as a cognitive mechanism, and scientific literacy and self-efficacy as interconnected outcomes. In conclusion, this study highlights the need for integrative, context-driven STEM learning models to support meaningful and transferable learning in sustainability education.

Keywords: Deep learning; Food security; Scientific literacy; Self-efficacy; STEM education

Introduction

Food security has become a central issue in achieving the Sustainable Development Goals (SDGs), particularly in ensuring sustainable and equitable food systems. According to Burki (2022), food security is defined through four interconnected dimensions: availability, access, utilization, and stability, which together determine the sustainability of food systems. However Cafiero et al. (2018) further explains that these dimensions are increasingly disrupted by climate change, population growth, and socio-economic inequality, resulting in systemic vulnerabilities rather than isolated problems.

This argument is supported by Carthy et al. (2018) who state that global food systems are characterized by inefficiencies and technological gaps that contribute to food waste and uneven distribution, while Prosekov et al. (2018) emphasize that food security challenges are closely linked to environmental degradation and structural socio-economic changes. These findings indicate that food security is not merely an agricultural issue, but a complex socio-scientific problem that requires systems thinking and interdisciplinary understanding, thereby positioning it as an epistemic domain within science education.

In the educational context, STEM education has been widely promoted as an approach capable of

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addressing such complex real-world problems by integrating multiple disciplines into meaningful learning experiences. Zhang et al. (2020) argue that STEM integration, particularly in agricultural and food system contexts, enables students to connect theoretical knowledge with real-life applications, thereby fostering interdisciplinary reasoning. This is reinforced by (Thies et al. (2024) who found that STEM-based food system projects significantly increase students' motivation and engagement when learning is connected to authentic societal issues. However, despite these advantages, Mudaly et al. (2023) critically note that STEM implementation often prioritizes curriculum conformity rather than deep conceptual understanding, while Tarlochan (2025) show that many STEM activities remain focused on procedural task completion. As a result, STEM learning frequently operates at a surface level, limiting students' ability to analyze complex issues such as food system sustainability and distribution inequality.

To overcome this limitation, deep learning as a pedagogical approach has been proposed as a means of fostering meaningful understanding and higher-order thinking. Biggs et al. (2022) define deep learning as a process in which learners actively construct meaning through conceptual integration, reflection, and knowledge transfer across contexts. To overcome this limitation, deep learning as a pedagogical approach has been proposed as a means of fostering meaningful understanding and higher-order thinking. Biggs et al. (2022) define deep learning as a process in which learners actively construct meaning through conceptual integration, reflection, and knowledge transfer across contexts. Fullan (2014) emphasizes that deep learning is essential for developing global competencies, including critical thinking, problem-solving, collaboration, and communication, which are required to address complex sustainability challenges.

Furthermore, Biggs et al. (2011) provide empirical and pedagogical evidence that learning approaches emphasizing metacognition, conceptual understanding, and knowledge transfer produce deeper and more meaningful learning outcomes compared to surface-level learning strategies. However, findings from synthesized studies such as Mostafa et al. (2025) indicate that although approaches like systems thinking can enhance sustainability understanding, they are rarely implemented within a coherent STEM-based framework. This suggests a gap between the theoretical potential of deep learning and its practical application in STEM education.

Another important issue lies in how learning outcomes are conceptualized in science education, particularly in relation to scientific literacy and self-efficacy. Norris et al. (2003) explain that scientific literacy involves not only understanding scientific concepts but also the ability to critically evaluate evidence and make informed decisions. This perspective is further reinforced by the Andersson (2017) which positions scientific literacy as a key competency for addressing complex global challenges such as sustainability and food systems. On the other hand, Bandura (1982) defines self-efficacy as an individual's belief in their ability to successfully perform tasks, and demonstrate that self-efficacy significantly influences students' motivation, persistence, and academic performance (Honicke et al., 2016). However, studies such as Coleman-Jensen et al. (2014) tend to focus primarily on scientific literacy, while Pajares (1994) emphasizes self-efficacy separately, resulting in a fragmented understanding of learning processes. This separation limits the ability to explain how students simultaneously develop cognitive understanding and confidence when engaging with complex real-world problems.

A similar fragmentation can be observed in the way food security is positioned within educational research. Studies such as Edwards (2018) show that food-based contexts can enhance STEM engagement, while Tripon (2025) highlights the role of sustainability-based learning in shaping students' awareness of food-related issues. However, these studies primarily treat food security as a contextual background rather than as a domain that actively structures knowledge construction. In contrast, broader research by Martin-Shields et al. (2019) focuses on food security from policy and socio-economic perspectives without integrating educational dimensions. Consequently, food security remains underutilized as a learning domain, and its potential to support deep learning, systems thinking, and interdisciplinary understanding is not fully realized within STEM education.

Taken together, the existing literature reveals a significant gap characterized by fragmentation across context, learning processes, and learning outcomes. Although studies Yao et al. (2026) have explored STEM education, deep learning, scientific literacy, self-efficacy, and food security individually, these components are rarely integrated within a unified framework. In particular, there is a lack of studies that simultaneously connect food security as a learning domain, STEM as an interdisciplinary approach, deep learning as a cognitive process, and both scientific literacy and self-efficacy as interconnected outcomes. As a result, current research provides only partial insights and fails to explain how meaningful learning can be designed to address complex real-world challenges such as food security within the SDGs context (Yang et al., 2025).

Based on these gaps, this study aims to systematically review and synthesize the integration of STEM-based deep learning in food security education for Sustainable Development Goals, with a particular focus on scientific literacy and self-efficacy. The novelty of this research lies in its effort to reconceptualize food security as an epistemic domain, integrate cognitive and affective learning outcomes within a single analytical framework, and propose an integrative conceptual model that connects context, process, and outcomes in science learning. By doing so, this study not only synthesizes fragmented evidence but also provides a theoretically grounded and pedagogically relevant framework for designing meaningful and transformative STEM-based learning in complex real-world contexts.

Method

This study employed a systematic literature review to synthesize research on STEM-based deep learning in food security education within the context of Sustainable Development Goals (SDGs), with particular emphasis on its relationship with scientific literacy and self-efficacy. The review followed the PRISMA 2020 framework to ensure transparency in the processes of identification, screening, eligibility assessment, and study inclusion (Page et al., 2021). This review was designed not only to identify relevant studies but also to map the fragmented nature of the existing literature. The topic integrates multiple constructs STEM education, deep or meaningful learning, food security education, SDGs, scientific literacy, and self-efficacy which are rarely examined simultaneously within a single study. Therefore, a staged and clustered search strategy was employed, followed by a systematic classification of studies into three categories: core synthesis studies, supporting theoretical or contextual sources, and excluded studies. This approach enabled a structured and transparent synthesis while maintaining conceptual clarity across diverse but interconnected research domains.

Search Strategy

The literature search was conducted using Scopus and ERIC as primary databases, with Google Scholar used as a supplementary source to identify additional relevant studies. These databases were selected because they support transparent searching, exportable records, and systematic documentation suitable for systematic review procedures. To avoid overly restrictive results and to address potential ambiguity in keyword usage, the search strategy employed clustered Boolean operators rather than a single rigid search string. A fully combined query (e.g., STEM education AND deep learning AND food security AND scientific literacy AND self-efficacy) would require all constructs to appear simultaneously in each article, which would significantly limit retrieval and contradict the purpose of this review namely, to synthesize fragmented evidence across related domains.

Instead, the search was structured around a core cluster: (“STEM education” OR “science education”) AND (“deep learning” OR “meaningful learning” OR “inquiry-based learning” OR “project-based learning” OR “higher-order thinking”) This core cluster was refined using outcome-related terms: (“scientific literacy” OR “science literacy” OR “self-efficacy”) and contextual terms: (“food security” OR “food system” OR “sustainability” OR “sustainability education” OR “SDGs”). Additional pedagogical keywords such as inquiry-based learning, project-based learning, and higher-order thinking were included to better capture the pedagogical dimension of deep or meaningful learning and to reduce ambiguity with artificial intelligence-related uses of the term “deep learning”.

The search was conducted progressively from broad to more refined combinations across databases. A total of 386 records were identified from Scopus (n = 234), ERIC (n = 32), and Google Scholar (n = 120). Google Scholar was used only as a supplementary source, and the results were limited to the most relevant records based on relevance ranking and topic alignment. These records were treated as identification records rather than unique datasets, as overlap across databases and iterative search strategies were expected. Therefore, the total number of identified records was not interpreted as the final dataset. The unique working corpus was established only after export, duplicate removal, and manual cleaning using Zotero.

Data Management and Record Cleaning

All identified records from Scopus and ERIC were exported in RIS format and imported into Zotero to ensure systematic reference management and traceability. Additional records identified from Google Scholar were included selectively and added manually only when their metadata such as title, author, publication year, journal name, and DOI could be verified to maintain data accuracy.

In Zotero, all records were systematically organized to detect and remove duplicates and to merge redundant entries across databases. This process was followed by an initial manual cleaning stage, in which each record was reviewed based on its title, abstract, document type, and keywords to ensure relevance to the scope of the review. Studies were excluded at this stage if they met one or more of the following criteria: (1) the study focused on deep learning as artificial intelligence or machine learning rather than pedagogical deep or meaningful learning; (2) the study was not situated within STEM education, science education, sustainability education, or formal learning contexts; (3)

the study addressed food security or agriculture solely from policy, economic, technological, health, or measurement perspectives without an educational component; (4) the study was a non-journal document, such as a book chapter, corrigendum, institutional report, or duplicate record; or (5) the study did not address relevant educational outcomes, such as scientific literacy, self-efficacy, motivation, higher-order thinking, or sustainability-related learning. Following duplicate removal and the application of these relevance criteria, the initial dataset of 386 records was reduced to 46 unique records, which were then retained as the working corpus for systematic screening using Rayyan.

Screening and Eligibility Assessment

The cleaned dataset of 46 records was imported into Rayyan for systematic screening based on title, abstract, and full-text evaluation. The screening process was conducted iteratively using three decision categories: include, exclude, and supporting (partially relevant). During the title and abstract screening stage, each record was assessed based on its alignment with the review focus, including STEM or science education, pedagogical deep or meaningful learning, scientific literacy or self-efficacy, and sustainability, food systems, or SDGs-related contexts. At this stage, 28 records were excluded because they were irrelevant, duplicated, non-educational, or focused on deep learning as artificial intelligence or machine learning rather than pedagogical learning. As a result, 18 studies were retained for full-text assessment.

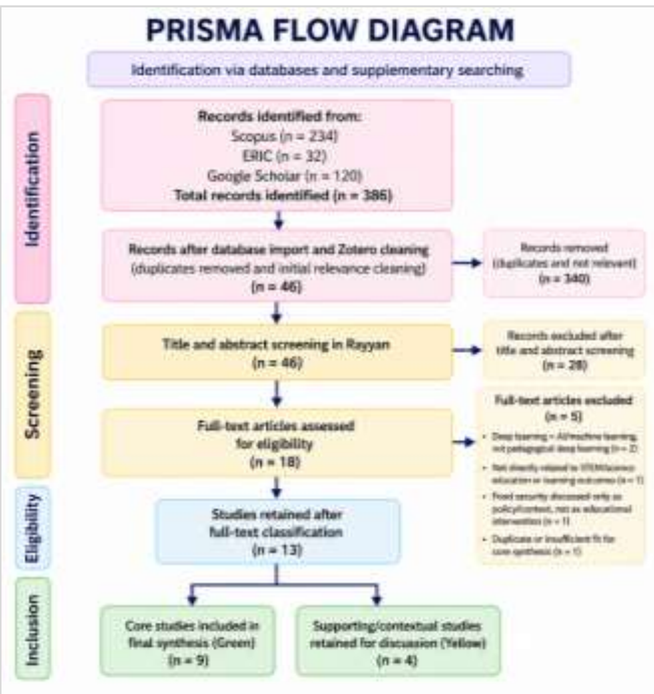

Figure 1. PRISMA flow diagram

During the full-text screening stage, the remaining studies were evaluated more comprehensively against the inclusion criteria. Five studies were excluded because they did not sufficiently meet the conceptual and methodological requirements of the review. Thus, 13 studies were considered eligible.

From these eligible studies, 9 studies were classified as core synthesis studies, as they directly aligned with the key constructs of the review. The remaining 4 studies were categorized as supporting or contextual sources, as they provided partial but relevant contributions to specific components of the framework, such as scientific literacy, self-efficacy, sustainability learning, or STEM integration. These supporting studies were not excluded; rather, they were used to strengthen the theoretical foundation and discussion. Therefore, only the 9 core studies were included in the final synthesis and quality appraisal.

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria were established to ensure that the selected studies were aligned with the focus of the review and the defined publication-year boundary. Studies were included if they were published between 2015 and 2025 and situated within STEM education, science education, sustainability education, or formal learning contexts.

Eligible studies were required to address at least one pedagogical process associated with deep or meaningful learning, such as inquiry-based learning, project-based learning, systems thinking, design thinking, service-learning, higher-order thinking, or interdisciplinary STEM learning. In addition, studies had to relate to one or more target outcomes, including scientific literacy, self-efficacy, motivation, reasoning, learning confidence, sustainability awareness, or other learning-related outcomes. Studies were also required to be connected to relevant contexts such as food security, food systems, agriculture, sustainability, environmental education, or SDGs-related learning.

Studies were excluded if they: (1) focused on deep learning as artificial intelligence, machine learning, or neural networks without pedagogical relevance; (2) addressed food security solely from policy, economic, health, or technological perspectives without an educational component; (3) were published outside the 2015–2025 range for empirical synthesis; or (4) were non-eligible document types, including duplicates, corrigenda, books, book chapters, institutional reports, or studies with unclear methodological information.

Foundational theoretical works (e.g., Bandura and Pajares) were retained exclusively for theoretical framing and were not included in the data extraction or quality appraisal processes. Only studies that met the inclusion criteria and demonstrated sufficient relevance during screening were classified as core synthesis studies, while partially relevant studies were categorized separately as supporting or contextual sources.

Table 1. Inclusion and Exclusion Criteria

Criterion	Included	Excluded
Publication year	Empirical or review articles published between 2015 and 2025	Articles outside 2015–2025 for empirical synthesis
Study context	STEM education, science education, sustainability education, formal learning contexts	Non-educational studies (e.g., food, agriculture, health, economics, or policy only)
Learning approach	Pedagogical deep/meaningful learning, inquiry-based learning, project-based learning, systems thinking, design thinking, service-learning, higher-order thinking	Deep learning as AI, machine learning, neural networks, or predictive analytics without pedagogical context
Outcomes	Scientific literacy, self-efficacy, motivation, reasoning, learning confidence, sustainability awareness, or related learning outcomes	No clear or relevant educational outcome
Contextual relevance	Food security, food systems, agriculture, sustainability, environmental education, SDGs-related learning	Food/security topics discussed only as policy or measurement background
Document type	Peer-reviewed journal articles or review articles suitable for synthesis	Duplicates, corrigenda, books, book chapters, institutional reports, incomplete or unclear records
Theoretical sources	Used only for theoretical framing (not included in synthesis)	Not included in data extraction or quality appraisal

Study Classification Procedure

After full-text screening, the eligible studies were systematically reorganized using a three-level classification procedure: core synthesis studies, supporting theoretical or contextual sources, and excluded studies. This step was essential to prevent the mixing of empirical evidence with theoretical references, policy reports, measurement-focused studies, duplicate records, and unrelated literature.

Core synthesis studies (n = 9) were defined as studies that directly contributed to the central focus of the review by integrating at least two or three key components, such as STEM or science education, pedagogical deep or meaningful learning, food systems or sustainability contexts, and relevant learning outcomes (e.g., scientific literacy, self-efficacy, motivation, or reasoning). These studies formed the primary basis for data extraction, quality appraisal, and final synthesis.

Supporting theoretical or contextual sources (n = 4) were retained when they provided meaningful contributions to specific constructs within the framework such as food security, sustainability learning, scientific literacy, or self-efficacy but did not present direct empirical evidence of STEM-based deep learning in food security education. These sources were not included in the main synthesis; instead, they were used to strengthen the conceptual foundation and support the interpretation of findings.

Table 2. Study Classification Procedure

Classification	Function in the Review	Decision Rule	Example of Placement
Core synthesis studies (n = 9)	Entered into data extraction, quality appraisal, and final synthesis	Strongly connected to at least two or three constructs (e.g., STEM education, sustainability/food systems, deep or meaningful learning, scientific literacy, self-efficacy)	Methods, results, and synthesis sections
Supporting theoretical/contextual sources (n = 4)	Used to strengthen introduction, theoretical framework, and discussion	Relevant to one key construct but not direct empirical evidence of STEM-based deep learning in food security education	Introduction and discussion sections
Excluded studies	Removed from extraction and quality appraisal	Duplicate, corrigendum, non-educational, AI/machine-learning-only deep learning, methodologically unclear, or too distant from review focus	Not included in synthesis

Excluded studies consisted of records that were duplicated, non-substantive, methodologically unclear, unrelated to the review focus, or that used the term "deep learning" in the context of artificial intelligence or machine learning rather than pedagogical learning. These studies were removed from further analysis.

This classification ensured that only empirically relevant studies were included in the data extraction and quality appraisal processes, while supporting sources were positioned appropriately within the theoretical framework and discussion to maintain conceptual clarity and analytical rigor.

Data Extraction Framework

Data extraction was conducted exclusively for the 9 core synthesis studies included in the final synthesis corpus. The extraction process employed a structured coding framework to ensure consistency, transparency, and comparability across studies.

Each study was systematically coded based on multiple domains, including bibliographic information, database source, educational context, research design, participants, learning approach, sustainability or food-related context, target outcomes, key findings, and relevance to the integrative framework. This multi-dimensional coding approach enabled a comprehensive understanding of how each study contributed to the overall synthesis.

Supporting theoretical and contextual sources were documented separately and were not included in the main extraction table or quality appraisal. This distinction was applied to prevent the overrepresentation of conceptual, theoretical, or background studies such as food security reports, self-efficacy frameworks, or general STEM literature as direct empirical evidence of STEM-based deep learning in food security education.

Table 3. Data Extraction Framework

Extraction Domain	Extracted Information	Purpose
Bibliographic identity	Author, year, title, journal, DOI/database source	To ensure traceability and avoid duplication
Study context	Country, educational level, subject area, learning setting	To identify the educational scope and context of the study
Research design	Experimental, quasi-experimental, survey, mixed-methods, review, case study	To assess methodological rigor and alignment
Participants	Number, level, learner type (e.g., students, teachers)	To determine population relevance
Learning approach	STEM integration, inquiry-based learning, project-based learning, service-learning, systems thinking, meaningful/deep learning	To identify pedagogical characteristics
Food/security/sustainability context	Food systems, agriculture, sustainability, SDGs, environmental education	To map contextual alignment with the review focus
Target outcomes	Scientific literacy, self-efficacy, motivation, reasoning, sustainability awareness, learning outcomes	To link studies with key variables
Key findings	Main findings relevant to learning processes and outcomes	To support thematic synthesis
Framework relevance	Full, partial, or contextual contribution	To classify each study's role in the synthesis

Quality Appraisal Procedure

Quality appraisal was applied exclusively to the 9 core synthesis studies included in the final synthesis corpus. Supporting theoretical sources, policy reports, food security measurement studies, duplicate records, corrigenda, and background-only literature were excluded from this stage, as they did not provide direct empirical evidence of STEM-based deep learning in food security education.

The appraisal process employed a structured rubric adapted from commonly used frameworks in systematic literature reviews to ensure consistency and methodological rigor. The rubric consisted of five criteria: (1) clarity of research objectives, (2) appropriateness of research design, (3) relevance to STEM or science education, (4) relevance to pedagogical deep or meaningful learning, and (5) relevance to key learning outcomes, including scientific literacy, self-efficacy, motivation, or sustainability-related outcomes.

Each criterion was evaluated using a three-level rating scale: low, moderate, or high. Studies were not required to achieve a high rating across all criteria, as the literature in this field is conceptually fragmented. However, each study was required to demonstrate a clear and meaningful contribution to at least one major component of the review framework to be retained in the synthesis.

Table 4. Quality Appraisal Rubric

Criterion	Low	Moderate	High
Clarity of research objectives	Aim is unclear, vague, or unrelated to the review focus	Aim is stated but only partially aligned with the review focus	Aim is explicit, clearly defined, and aligned with STEM/science education, sustainability, or learning outcomes
Appropriateness of research design	Research design is unclear or lacks justification	Research design is acceptable but limited in rigor or explanation	Research design is clearly described, justified, and appropriate for the research objectives
Relevance to STEM/science education	Minimal or indirect connection to STEM or science education	Partial relevance to STEM or science education	Strong and explicit focus on STEM or science education
Relevance to deep/meaningful learning	No clear pedagogical learning process identified	General or implicit learning process mentioned	Clear use of inquiry-based learning, PBL, systems thinking, meaningful/deep learning, or service-learning
Relevance to target outcomes	Outcomes are unclear or not relevant to the review focus	Outcomes are partially related to the review focus	Outcomes clearly include scientific literacy, self-efficacy, motivation, reasoning, or sustainability-related learning

Inter-Rater Reliability

To strengthen the reliability of the screening process, inter-rater checking was conducted during the title and abstract screening stage. A subset of 30% of the screened records (n = 46) was independently evaluated by a second reviewer using the same inclusion and exclusion criteria. Inter-rater agreement was calculated using Cohen's Kappa coefficient, which resulted in a value of 0.82, indicating strong agreement between reviewers. This level of agreement suggests a high degree of consistency in the application of screening criteria.

Table 5. Inter-Rater Reliability Procedure

Component	Description
Checked sample	30% of screened records (from n = 46)
Screening stage	Title and abstract screening
Agreement index	Cohen's Kappa coefficient
Kappa value	0.82
Interpretation	Strong agreement
Resolution method	Discussion until consensus

Any discrepancies between reviewers were resolved through discussion until consensus was reached. Importantly, the reliability check was conducted at the screening stage rather than only on the final included studies to ensure that the selection process was consistent and reliable prior to establishing the final synthesis corpus.

Data Synthesis

The final synthesis employed a thematic synthesis approach to integrate evidence from the 9 core synthesis studies. The synthesis did not assume that each study addressed all constructs simultaneously. Instead, each study was analyzed based on its contribution to the review framework, including STEM or science education, pedagogical deep or meaningful learning, food security or sustainability contexts, scientific literacy, and self-efficacy.

The synthesis was organized into two primary levels of contribution: full integration and partial integration. Full integration referred to studies that connected STEM or science education, a food-related or sustainability context, and at least one key learning outcome. Partial integration referred to studies that addressed two or three major components of the framework, such as STEM and scientific literacy, inquiry-based learning and self-efficacy, or sustainability and learning engagement.

Table 6. Data Synthesis

Synthesis Level	Definition	Function
Full integration	Studies connecting STEM/science education, food or sustainability context, and at least one key learning outcome	To identify studies with the strongest alignment to the review framework
Partial integration	Studies addressing two or three major constructs (e.g., STEM + literacy, inquiry + self-efficacy, sustainability + engagement)	To capture fragmented but meaningful contributions across studies

Supporting theoretical or contextual sources were not included in the main synthesis. Instead, they were used to strengthen the conceptual interpretation and discussion, ensuring that the synthesis remained grounded in empirical evidence while acknowledging the broader theoretical landscape. This approach enabled the review to demonstrate the fragmented nature of the literature while also identifying patterns of integration across studies, ultimately supporting the development of a coherent and integrative conceptual framework.

Result and Discussion

Overview of Reviewed Studies

The systematic literature review resulted in the inclusion of nine core studies in the final synthesis corpus, following a rigorous process of identification, screening, and eligibility assessment. These studies met the predefined inclusion criteria and were considered sufficiently relevant to the focus of this review, which integrates STEM-based learning, pedagogical deep or meaningful learning processes, food or sustainability-related contexts, and key learning outcomes such as scientific literacy and self-efficacy. The selection of these studies reflects an effort to capture the multidimensional nature of contemporary science education, particularly in relation to how cognitive, contextual, and affective dimensions are addressed within interdisciplinary learning environments.

However, a closer examination reveals that the contributions of these studies are not equivalent. To avoid overgeneralization and to represent the structure of the literature accurately, the synthesis was conducted using a two-level analytical stratification, namely: (1) full integration studies and (2) partial integration studies. This stratification is essential because the literature, although growing, remains conceptually fragmented and uneven in its integration of key constructs.

Table 7. Characteristics of Core Synthesis Studies (n = 9)

Author	Year	Context	Design
Thies et al.	2024	Food system STEM education	Experimental
Wang & Knobloch	2018	AFNR STEM education	Mixed-method
Edwards	2019	Food science education	Descriptive
Tripon	2025	Sustainable food education	Quantitative
Mudaly & Chirikure	2023	Global STEM education	Review
Dragoş & Mih	2015	Science education	Empirical
Honicke & Broadbent	2016	Academic learning	Systematic review
Green et al.	2022	Sustainability education	Empirical
Wu	2025	Science education (Asia)	Quantitative

As presented in Table 7, the reviewed studies demonstrate considerable diversity in both educational context and research design. The studies span multiple domains, including food systems, sustainability education, general science education, and academic learning. Methodologically, the literature is dominated by quantitative and experimental approaches, followed by mixed-method and review-based studies. This distribution indicates a strong emphasis on measurable outcomes and empirical validation.

However, this diversity does not necessarily lead to conceptual integration. Instead, it reveals that different studies tend to focus on specific aspects of the learning process, resulting in a body of literature that is broad in scope but uneven in depth. While some studies emphasize contextual relevance, others focus on pedagogical processes or learning outcomes, but only a limited number attempt to connect these components simultaneously.

To further clarify the analytical structure of the reviewed studies, Figure 2 presents the level of integration across the synthesis corpus. The figure distinguishes between full integration and partial integration studies, highlighting the extent to which each study connects key components of the framework, including STEM education, contextual learning (food/sustainability), pedagogical processes, and learning outcomes.

The figure shows that only a small number of studies approach full integration, while the majority remain partially integrated across specific domains. Studies categorized as full integration provide the closest alignment with the proposed framework, yet they still do not achieve complete conceptual integration. In contrast, partial integration studies tend to focus on isolated relationships, such as STEM and context, pedagogy and sustainability, or learning outcomes without contextual embedding.

This pattern leads to a critical conclusion: the existing literature is not merely limited in quantity but is structurally fragmented across three major domains, namely (1) contextual STEM learning, (2) pedagogical learning processes, and (3) cognitive–affective learning outcomes. These domains are often examined independently rather than as part of an integrated instructional system.

Importantly, no study has been identified that simultaneously integrates STEM-based learning, food security or sustainability contexts, pedagogical deep learning processes, and both scientific literacy and self-efficacy within a single, coherent model. Even studies categorized as full integration remain partial in their conceptual alignment. This gap represents the central contribution and novelty of the present review, which aims to move beyond fragmented evidence toward the development of an integrative framework.

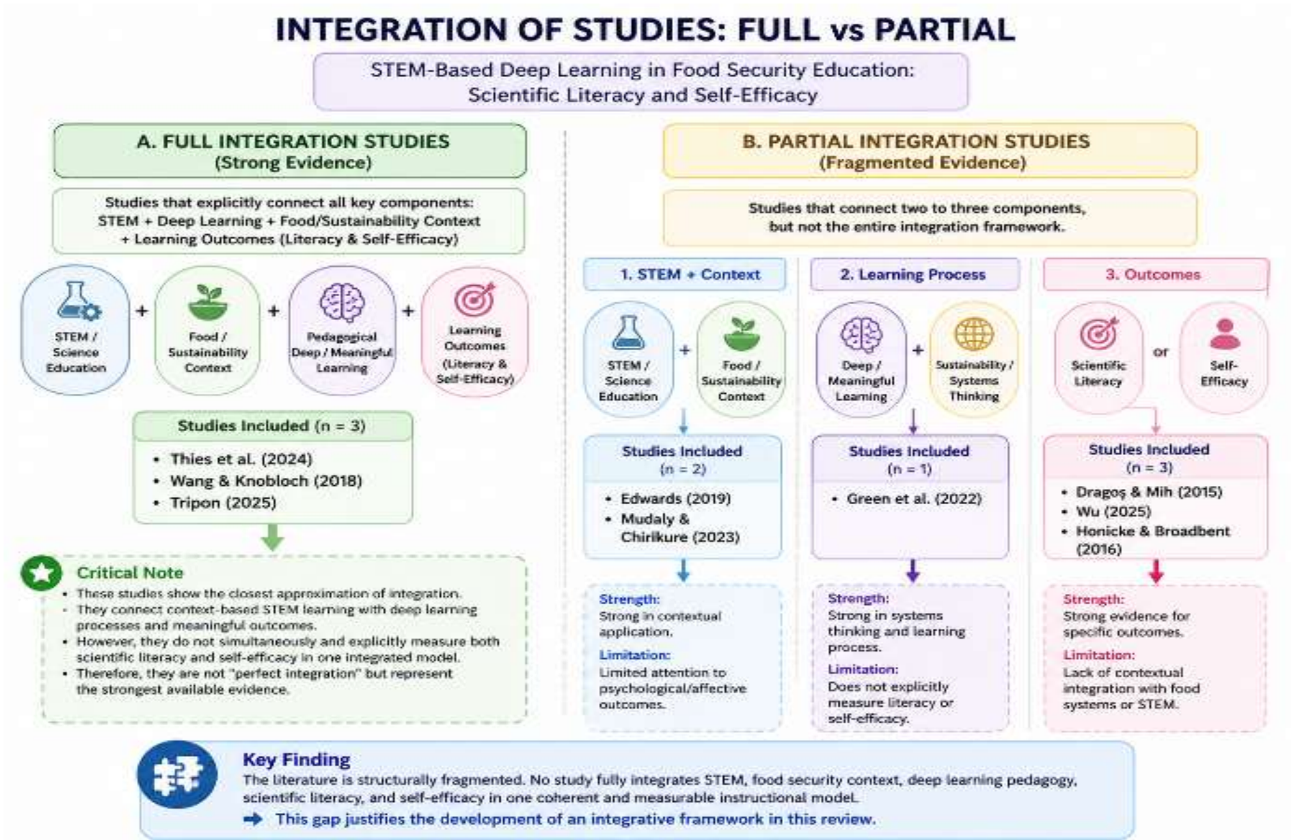

Figure 2. Integration of studies: full vs partial

Distribution of Research Focus and Methods

The distribution of research focus was analyzed based on the dominant contribution of each of the nine core studies included in the synthesis. The results indicate that context-based STEM learning, particularly within food systems, agriculture, and sustainability contexts, represents the largest proportion, accounting for four studies (44.4%). This group reflects a strong emphasis on the use of authentic, real-world contexts to support STEM learning. In contrast, studies focusing specifically on scientific literacy account for two studies (22.2%), while self-efficacy is explicitly addressed in one study (11.1%). The remaining two studies (22.2%) contribute to broader domains such as sustainability learning, systems thinking, and general STEM education perspectives.

Figure 3 illustrates that the literature is disproportionately concentrated on contextual applications of STEM learning, particularly in food and sustainability-related domains. While this indicates a growing recognition of the importance of real-world relevance in education, it also reveals a critical imbalance. Cognitive outcomes such as scientific literacy and affective constructs such as self-efficacy are comparatively underrepresented and, more importantly, rarely examined in conjunction with contextual learning. This suggests that current research tends to conceptualize learning as separated domains rather than as an integrated system connecting context, pedagogy, and outcomes.

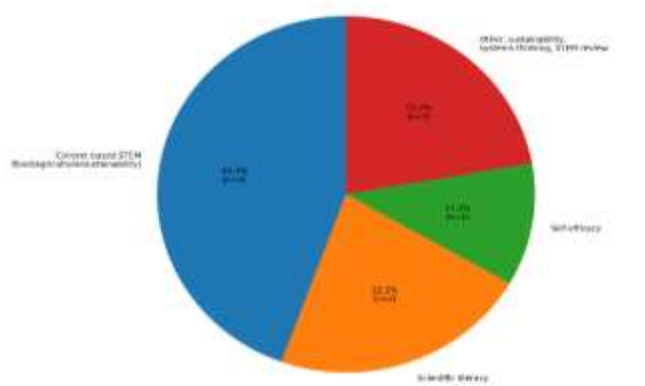

Figure 3. Distribution of research focus

From a methodological perspective, the reviewed studies demonstrate a balanced but fragmented distribution. Quantitative, empirical, and review-based approaches each account for two studies (22.2%), while experimental, mixed-method, and descriptive designs are each represented by one study (11.1%). This indicates that the field does not rely on a single dominant methodological paradigm but instead combines outcome-oriented, descriptive, and conceptual approaches.

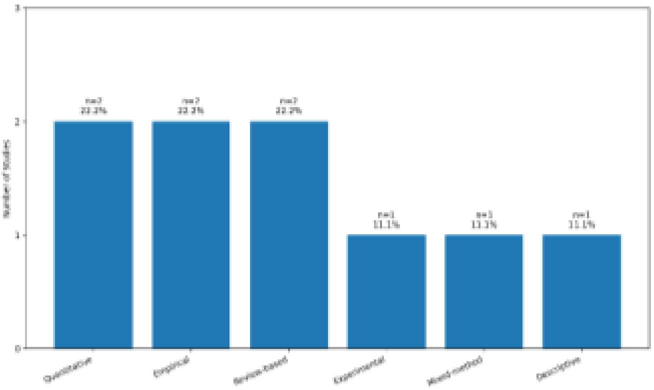

Figure 4. Distribution of research methods

Figure 4 shows that although quantitative and empirical designs remain important for establishing measurable learning outcomes, they tend to prioritize outputs over the exploration of underlying learning processes. The presence of review-based studies further indicates that the field is still in a stage of conceptual consolidation, requiring synthesis across fragmented evidence. Meanwhile, the limited use of mixed-method approaches suggests that current research has not sufficiently captured the interaction between cognitive, affective, and contextual dimensions of learning.

Taken together, these findings reinforce the central pattern identified in this review: the literature is not only diverse but also structurally fragmented. Contextual STEM learning is relatively well represented, yet it is rarely integrated with both cognitive outcomes (scientific literacy) and affective dimensions (self-efficacy). Methodologically, many studies demonstrate what works, but fewer explain how learning processes unfold in complex, real-world contexts. This imbalance highlights a critical gap and strengthens the need for an integrative framework that connects food security or sustainability contexts, STEM-based pedagogical processes, and cognitive–affective learning outcomes within a coherent instructional model.

Thematic Synthesis of Reviewed Studies (Final Revised)

To move beyond descriptive distribution patterns, a thematic synthesis was conducted to examine how key constructs STEM education, deep or meaningful learning, contextual learning (food systems or sustainability), scientific literacy, and self-efficacy are conceptualized and interrelated across the reviewed studies. The synthesis was conducted exclusively based on the nine core studies included in the final corpus. Supporting theoretical and contextual sources were used only to strengthen interpretation and were not included as empirical evidence in the thematic table, in order to maintain methodological consistency.

As summarized in Table 8, STEM consistently emerges as a dominant interdisciplinary approach within the reviewed studies. Research by Thies et al. (2024) and Wang et al. (2022), for example, demonstrates that STEM-based learning within food and agricultural contexts can enhance systems thinking and problem-solving. However, the extent to which these improvements translate into integrated learning outcomes remains limited. In most cases, STEM is implemented as a structural or contextual approach rather than as a fully integrated system connecting cognitive, affective, and contextual dimensions.

Contextual learning, particularly through food systems and sustainability, is also strongly represented. Studies such as Tripon (2025) and Edwards (2012) highlight the role of real-world contexts in increasing student engagement and relevance. Nevertheless, these contexts are not consistently used to facilitate deeper cognitive processes such as reflection, conceptual integration, or knowledge transfer. As a result, there is a mismatch between the complexity of the context and the depth of learning processes it supports.

A similar limitation is observed in the treatment of deep or meaningful learning. Although it is frequently implied in studies involving inquiry, systems thinking, or sustainability learning (Green et al., 2022), explicit operationalization remains limited. Most studies do not clearly describe how deep learning processes are structured, assessed, or sustained in practice. This indicates a gap between pedagogical intention and implementation.

Scientific literacy and self-efficacy further illustrate the fragmented structure of the literature. Scientific literacy is moderately represented as a cognitive outcome, particularly in studies such as Dragoș et al. (2015) and Wu (2025). In contrast, self-efficacy appears only minimally and is typically treated as an isolated affective variable rather than as part of an integrated learning system (Honicke et al., 2016). The lack of interaction between these constructs limits the ability to understand how cognitive and affective processes jointly influence learning.

Taken together, these findings confirm that the literature provides strong but disconnected evidence. Key components of learning context, pedagogy, and outcomes are often examined in parallel rather than as an integrated system. Importantly, no study within the synthesis fully integrates STEM-based learning, contextual learning (food/sustainability), deep learning processes, and both scientific literacy and self-efficacy within a single instructional model. This structural fragmentation represents the central gap addressed by this review and forms the basis for the proposed integrative framework.

Table 8. Thematic Synthesis of Core Studies (n = 9)

Theme	Description	Evidence Pattern	Supporting Core Studies	Key Insight
STEM as interdisciplinary approach	STEM integrates multiple disciplines to address real-world problems	Strong presence across context-based studies, but varies in depth of integration	Thies et al.; Wang & Knobloch; Edwards; Mudaly & Chirikure	Promotes systems thinking, but lacks consistent linkage to outcomes
Contextual learning (food/sustainability)	Food systems and sustainability provide authentic learning contexts	Dominant contextual approach in STEM learning	Thies et al.; Wang & Knobloch; Edwards; Tripon	Strong context, but not fully used to drive deep learning processes
Deep/meaningful learning processes	Learning involves reflection, integration, and knowledge transfer	Limited explicit operationalization in empirical studies	Green et al.; Tripon; Wang & Knobloch	Often implied, but rarely designed explicitly
Scientific literacy as cognitive outcome	Involves reasoning, evidence evaluation, and decision-making	Moderately represented as a primary learning outcome	Dragoş & Mih; Wu	Strong cognitive focus, but weak integration with affective domain
Self-efficacy as affective dimension	Influences motivation, persistence, and learning engagement	Minimally represented and often isolated	Honicke & Broadbent	Important, but rarely embedded in STEM learning design
Fragmentation in literature	Constructs are studied separately rather than integratively	Majority of studies address only 1–2 constructs	Cross-study synthesis (all 9 studies)	Lack of holistic learning model
Need for integrative framework	Integration of context, pedagogy, and outcomes is required	No study fully integrates all constructs simultaneously	Cross-study synthesis	Learning must be conceptualized as an interconnected system

Integration Pattern of Learning Components (Revised Final)

To further examine the structure of the reviewed literature, an analysis was conducted to identify the extent to which key learning components are integrated within the nine core studies. The analysis focused on four main components: (1) STEM-based learning, (2) deep or meaningful learning processes, (3) contextual learning (food systems or sustainability), and (4) learning outcomes, including scientific literacy and self-efficacy.

Table 9. Integration Pattern of Learning Components (n = 9)

Integration Category	Criteria	Number of Studies	Proportion	Interpretation
Full Integration (closest)	Studies connecting STEM, contextual learning, pedagogical processes, and at least one learning outcome	3 studies	33.3%	Rare; represents the closest alignment with the integrative framework
Partial Integration	Studies addressing 2–3 components without full alignment	6 studies	66.7%	Dominant pattern; indicates structural fragmentation

The classification presented in Table 9 was based on the extent to which each study explicitly addressed the four key components of this review. Studies were categorized as full integration (closest) when they demonstrated a clear connection between STEM-based learning, contextual applications (food or sustainability), pedagogical processes associated with deep learning, and at least one learning outcome. Based on this criterion, studies such as Thies et al. (2024), Wang et al. (2018), and Tripon (2025) were classified within this category. However, it is important to note that even these studies do not fully integrate all components simultaneously, particularly in relation to the combined measurement of scientific literacy and self-efficacy.

The majority of studies were classified as partial integration, as they addressed only two or three components of the framework. These include studies such as Edwards (2019), Green et al. (2022), Mudaly et al. (2023), Dragoş et al. (2015), Honicke et al. (2016), and Wu (2025). These studies provide valuable insights into specific dimensions of learning, but do not establish a comprehensive connection between context, pedagogy, and outcomes.

This classification clearly demonstrates that the literature is dominated by partially integrated studies, with only a limited number approaching integrative alignment. Importantly, this finding confirms that fragmentation is not incidental, but structural within the literature. This structural fragmentation reflects a deeper conceptual issue. The limitation of the literature does not lie in the absence of evidence, but in the lack of coherence across studies. Different studies operate within separate conceptual domains contextual learning, pedagogical processes, or learning outcomes without systematically connecting them. As a result, even when individual studies report positive findings, these results remain difficult to synthesize into coherent instructional models.

Therefore, the primary gap identified in this review is not the lack of research, but the absence of an integrative framework that connects STEM-based learning, contextual applications (food or sustainability), deep learning processes, and both cognitive and affective learning outcomes. This gap forms the basis for the conceptual contribution of the present study.

Proposed Integrative Framework

In response to the limitations identified in the thematic synthesis and integration pattern analysis, this study proposes an integrative framework that connects learning context, pedagogical processes, and learning outcomes. The proposed framework, presented in Figure 5, was developed based on the recurring patterns and gaps identified in Table 8 and Table 9. The synthesis revealed that STEM education, deep or meaningful learning, food security or sustainability contexts, scientific literacy, and self-efficacy were mostly examined in partial or isolated ways across the reviewed studies. Therefore, the framework was constructed as a conceptual response to this fragmentation by integrating these components into a more coherent learning system.

In this framework, food security is positioned as an epistemic learning context, meaning that it is not treated merely as a background theme but as a domain through which students construct knowledge, analyze real-world problems, and connect scientific concepts with sustainability challenges. STEM functions as an interdisciplinary structure that organizes learning across science, technology, engineering, and mathematics, while deep or meaningful learning serves as the cognitive mechanism through which students engage in reflection, conceptual integration, evidence-based reasoning, and knowledge transfer.

Scientific literacy and self-efficacy are conceptualized as interconnected learning outcomes rather than separate variables. Scientific literacy represents the cognitive capacity to understand concepts, evaluate evidence, and make informed decisions, whereas self-efficacy represents the affective capacity that supports confidence, persistence, and engagement in complex learning tasks. By linking these components, the proposed framework shifts the understanding of learning from a linear input–output model toward a dynamic system in which context, cognition, pedagogy, and affect interact to produce meaningful and transferable knowledge.

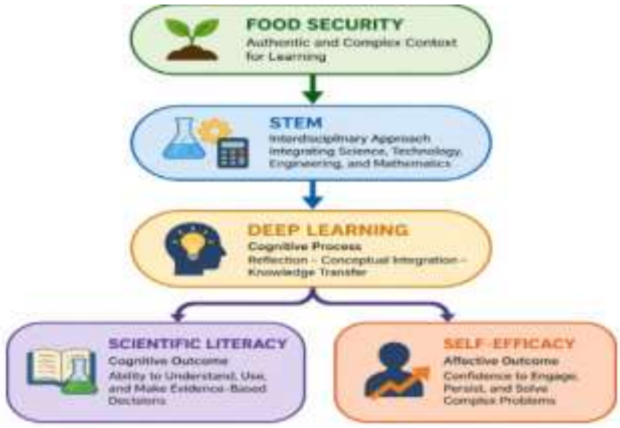

Figure 5. Integrative framework of STEM-based deep learning in food security education

This framework does not emerge solely from the authors' assumptions, but from the structural fragmentation identified across the reviewed studies. While several studies provide partial evidence of STEM integration, contextual learning, scientific literacy, or self-efficacy, no study fully integrates all components into one coherent and measurable instructional model. Therefore, the proposed framework contributes to the literature by offering a conceptual basis for future empirical studies that aim to design and test STEM-based deep learning in food security education, especially in sustainability-oriented science learning contexts.

Fragmented Yet Complementary Literature

The analysis of the reviewed studies reveals a paradoxical yet structurally significant condition within the literature. The field is simultaneously rich in empirical and theoretical evidence, yet remains fundamentally fragmented in its conceptual and pedagogical orientation. This condition is evident from the synthesis of the nine core studies, which collectively demonstrate strong but uneven contributions across contextual learning, pedagogical processes, and learning outcomes.

On one hand, several studies provide robust evidence on the effectiveness of STEM-based learning in enhancing systems thinking, problem-solving, and contextual understanding, particularly when embedded in real-world domains such as food systems and sustainability (Thies et al., 2024; Wang & Knobloch, 2018; Tripon, 2025). On the other hand, studies focusing on scientific literacy and self-efficacy offer strong insights into cognitive and affective learning outcomes, highlighting the importance of reasoning, confidence, and engagement in learning processes (Dragoş et al., 2015; Wu, 2025; Honicke et al., 2016). In addition, broader perspectives from sustainability learning and STEM education reviews further reinforce the importance of interdisciplinary and systems-oriented approaches (Green et al., 2022; Mudaly et al., 2023).

However, despite the strength of these individual contributions, the literature demonstrates a clear lack of integration across these domains. Each strand of research tends to operate within its own conceptual boundary, resulting in what can be described as parallel knowledge development rather than cumulative or integrative knowledge construction. Context-based STEM learning, pedagogical deep learning processes, and cognitive–affective outcomes are frequently examined in isolation, with limited attempts to connect them within a unified instructional framework.

More critically, this fragmentation reflects a deeper methodological issue. Most studies are designed around isolated variables or limited relationships, rather than complex learning systems. STEM is often treated as an instructional approach, contextual learning (food systems or sustainability) as a thematic domain, scientific literacy as a measurable cognitive outcome, and self-efficacy as an affective construct. Yet, very few studies attempt to explain how these components interact dynamically within the same learning environment. As a result, learning is often implicitly modeled as a linear cause–effect relationship rather than as a dynamic system involving feedback loops between context, cognition, and affect.

This condition suggests that the limitation of the literature does not lie in the absence of evidence, but in the absence of coherence. While existing studies provide strong insights within their respective domains, they remain insufficient to explain how meaningful learning emerges in complex, real-world contexts such as food security or sustainability issues. Therefore, the key challenge for future research is not merely to generate additional evidence, but to develop and empirically test integrative frameworks that connect these fragmented insights into a coherent pedagogical model.

Reframing Food Security as an Epistemic Context

A central finding of this study is the need to reconceptualize food security from a contextual background into an epistemic domain that actively shapes the structure of learning. Although the reviewed studies consistently acknowledge the complexity of food security and sustainability issues, most of them position these contexts as illustrative or thematic backgrounds rather than as foundations for knowledge construction. As a result, the role of context in learning remains largely descriptive rather than generative.

Supporting literature outside the core synthesis further reinforces the multidimensional nature of food security, highlighting its dependence on interrelated factors such as production systems, access, distribution, climate change, and socio-economic inequality. However, these contributions are predominantly diagnostic, focusing on explaining what the problem is and why it occurs, without sufficiently addressing how such complexity can be transformed into meaningful learning experiences. Consequently, there is a disconnect between the complexity of real-world issues and the way they are pedagogically utilized.

This limitation becomes more evident when examined alongside STEM-based learning approaches identified in the core studies. While STEM provides a powerful interdisciplinary structure for addressing complex problems, its application is often instrumental rather than epistemic. In many cases, STEM is used to improve engagement or conceptual understanding, but not to cultivate systemic and reflective ways of thinking that mirror the complexity of real-world challenges. This results in a fundamental mismatch: complex, interconnected problems are addressed through simplified instructional designs that do not fully leverage their epistemic potential.

From a deep or meaningful learning perspective, this mismatch is particularly critical. Deep learning requires learners to engage in reflection, conceptual integration, and knowledge transfer across contexts. However, such processes are unlikely to emerge when learning contexts are treated as passive backgrounds. Instead, they require contexts that function as epistemic drivers, compelling learners to question assumptions, analyze evidence, and construct knowledge through inquiry and reasoning. In this sense, food security has the potential to act as a powerful epistemic domain, as it inherently demands interdisciplinary thinking, systems analysis, and decision-making under uncertainty.

Therefore, the key issue is not the relevance of food security as a learning context, but the way in which it is conceptualized and operationalized within instructional design. The existing literature has successfully established its importance as a real-world issue, but has not fully exploited its potential as a structuring mechanism for learning processes. Reframing food security as an epistemic context allows it to move beyond a thematic role and instead function as a catalyst for deep, integrative, and transferable learning.

Integrating Cognitive and Affective Dimensions: Scientific Literacy and Self-Efficacy

Another critical limitation identified in the literature is the persistent separation between cognitive and affective dimensions of learning. Within the reviewed studies, scientific literacy is consistently positioned as a central cognitive outcome encompassing conceptual understanding, evidence evaluation, and informed decision-making while self-efficacy is treated as an affective construct that shapes motivation, persistence, and engagement (Dragoș & Mih, 2015; Wu, 2025; Honicke & Broadbent, 2016). Broader theoretical work further reinforces the importance of both constructs, yet their integration remains largely absent in empirical instructional designs.

Despite their individual significance, these constructs are rarely examined within a unified framework. Most studies treat them as independent variables or outcomes, resulting in a fragmented understanding of how learning actually unfolds. This separation is particularly problematic in the context of deep or meaningful learning, which inherently requires the interaction between cognitive processing and affective regulation.

Deep learning involves engaging with complex problems, reflecting on understanding, and transferring knowledge across contexts. These processes are cognitively demanding and often involve uncertainty, ambiguity, and sustained effort. Under such conditions, self-efficacy functions as an enabling mechanism: learners with higher confidence are more likely to persist, take intellectual risks, and engage in higher-order thinking. Conversely, learners with low self-efficacy tend to disengage or avoid challenging tasks, thereby constraining the depth and transferability of their learning.

At the same time, scientific literacy without self-efficacy is insufficient for meaningful action. Learners may possess the knowledge and reasoning skills to evaluate evidence, yet lack the confidence to apply these competencies in real-world decision-making. This indicates that scientific literacy and self-efficacy are not merely complementary, but interdependent constructs that must be co-developed within learning environments.

However, the literature has not yet fully articulated or operationalized this relationship. While theoretical perspectives acknowledge the importance of integrating cognitive and affective dimensions, empirical studies rarely embed both constructs within the same instructional design or assess their interaction systematically. As a result, the mechanisms through which cognition and affect co-evolve in complex learning contexts remain underexplored.

Taken together, this gap suggests that current research tends to assume rather than design the conditions necessary for meaningful learning. Addressing this limitation requires moving beyond outcome-based measurement toward instructional models that explicitly integrate scientific literacy and self-efficacy as interacting dimensions within STEM-based, context-rich learning environments. This need directly informs the integrative framework proposed in this study.

Toward Transformative Learning Design

The findings of this study underscore the need for a fundamental shift from fragmented, outcome-oriented approaches toward integrative and systemic learning design. Building on the thematic synthesis and integration analysis, the proposed framework connects food security as an epistemic context, STEM as an interdisciplinary structure, deep learning as a cognitive mechanism, and scientific literacy and self-efficacy as interdependent outcomes. This configuration moves beyond treating these elements as separate variables and instead positions them as mutually reinforcing components within a coherent learning system.

This perspective challenges the dominant linear model of learning, which assumes that instructional inputs directly produce measurable outcomes. In contrast, the proposed framework conceptualizes learning as a dynamic system in which context, cognition, and affect interact continuously through feedback processes. Within this system, context provides epistemic grounding and relevance; interdisciplinary STEM structures organize inquiry and problem-solving; deep learning processes enable reflection, conceptual integration, and knowledge transfer; and affective factors, particularly self-efficacy, sustain engagement and persistence in complex tasks. Outcomes are therefore not end points, but evolving states that both result from and feed back into ongoing learning processes.

Importantly, this shift requires intentional and aligned pedagogical design. Presenting complex, real-world problems alone is insufficient. Learning environments must be deliberately structured to support how students engage with complexity. This includes designing tasks that demand evidence-based reasoning, embedding iterative reflection and conceptual integration, and incorporating scaffolds that build self-efficacy (e.g., mastery experiences, formative feedback, and graduated challenge). Such alignment ensures that cognitive demands (scientific literacy) and affective supports (self-efficacy) are developed in tandem, rather than in isolation.

Without this level of integration, the potential of STEM-based deep learning to generate transformative outcomes remains constrained. Consequently, the central challenge is not merely the adoption of interdisciplinary approaches, but the orchestration of context, process, and outcomes into a coherent design that mirrors the complexity of real-world problems.

This framework has implications for designing sustainability-oriented STEM curricula aligned with Sustainable Development Goals (SDGs), particularly in developing contexts. Furthermore, this study moves beyond variable-based analysis toward a system-based learning design that emphasizes the interaction between context, cognition, and affect.

Conclusion

This systematic literature review concludes that STEM-based food security education is an emerging but still fragmented research area. The final synthesis of 9 core studies shows that several studies have connected STEM learning with food systems, agriculture, sustainability, SDGs, motivation, inquiry, and scientific literacy. However, no study was found to fully integrate STEM-based deep learning, food security education, scientific literacy, and self-efficacy into one complete and measurable instructional model. The main finding of this review is that food security should not only be treated as a background issue, but as an epistemic learning domain. This means food security can become a central context through which students learn science concepts, analyze real-world problems, connect STEM disciplines, evaluate evidence, and develop sustainability-oriented decision-making. In this position, food security becomes more than a topic; it becomes a meaningful learning space for developing students' cognitive and affective competencies. This review also found that scientific literacy and self-efficacy are still under-integrated in STEM-based food security education. Scientific literacy appeared mainly in studies on STEM-integrated science learning and sustainability awareness, while self-efficacy appeared mainly in studies related to inquiry, motivation, and hands-on STEM learning. This indicates that current research tends to address these outcomes separately rather than combining them in one integrated learning design. Therefore, the novelty of this review lies in proposing an integrative framework that connects food security and SDGs as the learning context, STEM-based deep learning as the pedagogical process, and scientific literacy and self-efficacy as complementary learning outcomes. This framework can help future researchers and educators design learning models that are more contextual, interdisciplinary, measurable, and relevant to sustainability challenges. This review has several limitations. First, the final synthesis was based on 9 core studies, which reflects the specificity and limited development of this research field. Second, the reviewed studies were geographically varied and did not strongly represent Indonesian or Southeast Asian contexts. Third, the operationalization of deep learning, scientific literacy, and self-efficacy differed across studies, making direct comparison difficult. Future research should therefore develop empirical interventions that test this integrative framework in local contexts, especially through mixed-methods, quasi-experimental, or design-based research. Future studies also need to measure both cognitive outcomes such as scientific literacy and affective outcomes such as self-efficacy within the same STEM-based food security learning model.

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The authors declare no conflict of interest.

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